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# DEVELOPMENT OF NONDESTRUCTIVE TESTING TECHNIQUES FOR PLATED-THROUGH HOLES IN MULTILAYER PRINTED CIRCUIT BOARDS



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16. ABSTRACT
The objective is to develop a NDT system with the capability to interrogate plated-through holes as small as 0.51 mm inside diameter, and detect defects such as holes, voids, cracks, thin spots, etc., that reduce the current-carrying capability of plated-through interconnects by twenty percent or more.

Efforts were directed toward the design and fabrication of magnetic circuitry mutual coupling probes and to evaluate the effectiveness of these devices for detecting defects in multilayer board plated-through holes. Two 1.52 mm probes and one 0.75 mm probe were designed and fabricated using the mutual coupling principle. It appears practical to fabricate probes with tip diameters down to about 0.51 mm by a direct extension of the same processing techniques.

While results are not conclusive, a considerable amount of original, practical information was obtained. A serious handicap of the probes designed is the extremely large mutual coupling signal generated from the overall hole wall itself. To distinguish between different types of defects is very difficult because of the high output signals and extreme sensitivity of the probes.

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DEVELOPMENT OF NONDESTRUCTIVE TESTING TECHNIQUES FOR PLATED-THROUGH HOLES IN MULTILAYER PRINTED CIRCUIT BOARDS

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SUMMARY

A general need exists for a device which is capable of nondestructively testing plated-through holes in multilayer printed circuit boards to detect the presence of certain critical structural defects. The defects in question are separations between the plated-through-hole wall and internal conductor pads, and voids, cracks, and thin spots in the plated wall itself. Unless such defects cause a complete discontinuity in the multilayer board, none could be detected by electrical functional tests and structurally inferior plated-through-hole interconnections of questionable reliability would be put into service.

Prior studies carried out on NASA Contract NAS8-11288 indicated that at least the separation type defect was detectable in simulated plated-through holes by a mutual coupling probe technique. Mutual coupling probes were constructed with miniaturized figure "8" coils for the excitation and sensor circuits to generate and pick up the external coupling magnetic fields. These probes were very fragile and provided only microvolt level output signals.

A new concept was proposed to take advantage of the mutual coupling principle and overcome the drawbacks with the figure "8" coil design. The new approach called for magnetic circuitry to carry the coupling fluxes to and from the external field areas at the probe tip. This meant that the small diameter probe tip (to be inserted in the plated-through holes for testing) could be a solid structure made up of only a high permeability ferrite material and metallic shielding. Thus, the small tip would be quite rugged and durable. Also, the magnetic circuitry could be extended from the probe tip to a much larger body which would remain outside the holes being tested. In the probe body much larger and more powerful coils could link the associated electronic circuitry with the magnetic circuitry paths to the tip.

This program was concerned with an effort to design and fabricate magnetic circuitry mutual coupling probes and to evaluate the effectiveness of these devices for detection of all of the above mentioned critical structural defects in actual multilayer board plated-through holes.

A proof-of-principle experiment was successfully carried out with the essential components of a magnetic circuitry mutual coupling probe and a simulated separation defect. A large scale magnetic probe was then constructed and further experiments as to basic operating characteristics and shielding requirements were conducted. The initial design for a probe with a single pair of magnetic circuits, one for excitation and one for sensing was then developed.

Several of these "single" probes with tips of 0.060 and 0.030 in. diameter were fabricated. Combinations of special machining and processing techniques were developed to successfully fabricate these miniature devices. Key steps were (1) ultrasonic impact grinding to form the small ferrite shapes and (2) electroless and electrolytic copper plating of the external probe shielding.

The single probes were evaluated with simulated separation defects and on actual multilayer boards with intentionally built-in defects of all the critical types. These test boards were specially fabricated for this program by modifying the normal processes so as to create the required plated-through-hole defects.

Because the single probe design appeared to be limited in its sensitivity to most of the defect types due to an unexpectedly high background signal from the overall plated-through-hole wall, a new probe configuration was designed in an attempt to overcome this problem. This probe contained two pairs of excitation and sensor circuits to create two separate external mutual coupling fields on opposite sides of the tip. A 0.060 in. diameter "double" probe was successfully fabricated by the same processing techniques developed for the single probes. Evaluation of the double probe on the test multilayer boards indicated some improvement in sensitivity over the single probe. However, a practical level of sensitivity to all of the defect types was not obtained.

The magnetic circuitry mutual coupling probes were shown to be distinct improvements over previous mutual coupling devices in two respects. First, the finished probes including the small diameter tips were very sturdy, rugged, and generally resistant to damage by normal usage. Second, the magnetic circuitry configuration does make possible some three orders of magnitude improvement in power levels with output signals on the order of tens of millivolts as opposed to a few microvolts. However, with the specific magnetic circuitry probe designs evaluated on this program, the sensitivity to most of the critical defects is impracticably small because of the large signal voltage generated by the overall wall in actual multilayer board plated-through holes.

# INTRODUCTION

As the use of multilayer printed circuit boards increased over the past 10 or 12 years, interest has grown in effective nondestructive testing techniques to augment conventional quality assurance methods. Such testing is particularly desirable because most multilayer board applications have been for military and aerospace hardware where uniform high quality and long-term reliability are paramount. Since multilayer circuit boards are essentially three-dimensional wiring networks, the ultimate failure modes are electrical discontinuities (opens) or electrical leakages (shorts). When electrical opens or shorts exist in the multilayer board as fabricated, the problem is relatively straightforward since the failures then can ordinarily be detected electrically by functional testing. A much more difficult situation arises when the multilayer board contains a structural defect which does not presently cause an open or short, but does represent a point of weakness which may subsequently fail after aging or an accumulation of service stresses.

In multilayer circuit boards, the plated-through holes which provide layer-to-layer electrical interconnections are by far the most critical sites for structural defects which can jeopardize reliability. Typical hole sizes are in the 0.030 to 0.100 in. range, but can be as small as 0.025 or 0.020 in. In the hole wall plating itself there can be localized voids, cracks, thin spots or inclusions of foreign material which do not completely interrupt the electrical pathway along the wall parallel to the hole axis from layer-to-layer of printed circuitry. Such a defective hole could still test good, i.e., show electrical continuity, but be weaker mechanically than a defect-free hole. Also, there can be the case where the hole wall plating is sound, but a structural defect exists in the form of a separation or gap between the plating and one or more of the internal conductor termination pads through which the hole passes and thereby interconnects with electrically. If the gap exists for anything less than the full circumferential interface between the hole wall plating and the internal pad, there is still electrical continuity. Again, however, the hole-to-pad structure is much weaker mechanically than a defect-free interconnection.

All of the defects just described are potential latent failures in multilayer boards which appear good by conventional inspection and functional testing methods. When later subjected to mechanical stresses which arise from vibration, temperature changes, etc., during service, such structurally-weak plated-through holes can fracture and create a physical discontinuity which is manifested as an electrical open or intermittent. Experience in the industry has shown that just this chain of events is the greatest hazard to the functional reliability of multilayer printed circuit boards. Unfortunately, the particular plated-through hole defects in question can readily arise from vagaries in the series of complex processes involved in the fabrication of multilayer boards.

Since structural defects can have such a critical effect on the reliability of multilayer board plated-through holes, considerable effort has been expended on means to prevent and to detect those types discussed above which are not necessarily revealed by electrical continuity testing. Prevention usually takes the form of painstaking and costly process control programs. Detection methods are generally indirect and typically involve destructive examination of integral test tabs from each board or of sample boards sacrificed from each production lot. At best, indirect methods provide only a statistical confidence that any given board is free of structurally defective plated-through holes.

Nondestructive testing techniques have, of course, been pursued for direct detection of defective plated-through holes. Certain of these techniques have been successfully developed to detect some of the critical types of defects in question. For example, precision electrical resistance measurements across the plated-through hole from one side of the board to the other can be used to detect defects such as transverse cracks which are physically separated, large voids, and thin spots. But, defects such as longitudinal cracks (or physically closed cracks in any orientation) and hole-to-pad separations are totally undetectable by this method. Various X radiography techniques (television X ray, laminography, steromicro-radiography, etc.) can be used to reveal large voids and some other gross defects, but are severely limited by geometrical shielding effects in and about the plated-through holes. Other approaches such as infrared, dye penetrants,and ultrasonics have been explored, but all are useful to detect only some of the more gross defects under certain conditions. In summary, it can be stated that presently no nondestructive testing technique is available which can detect all of the plated-through hole defects of interest, except possibly for the technique of mutual coupling. In particular, mutual coupling is the only known means to nondestructively detect the critical hole-to-pad separation defect.

The mutual coupling principle was applied to testing of multilayer board plated-through holes by workers at the Illinois Institute of Technology on NASA Contract NAS8-11288. Miniaturized probes down to 0.020 in. OD were fabricated and shown to be capable of detecting the gap or separation type defect in simulated plated-through holes. No other defect types, simulated or in actual multilayer boards, were tested on that program. The mutual coupling probe devices were constructed by mounting two small figure "8" electrical coils in a probe tip to generate and sense the external magnetic fluxes. Ferromagnetic shielding materials and compensating coils also had to be employed to reduce direct coupling or noise in the probe. Mutual coupling probes so constructed on a scale suitable for insertion into multilayer board plated-through holes were difficult to fabricate and assemble, extremely fragile and of very low sensitivity. The best output signals reported for such electrical coil mutual coupling probes when used to measure simulated separation defects were only a few microvolts.

Even though the NASA Contract NAS8-11288 effort indicated that hole-to-pad separation defect, and presumably the other defect types, could in principle be detected; mutual coupling probe devices based on miniature electrical coils and ferromagnetic shielding materials were not subsequently reduced to practice or made commercially available. This was primarily because of the inherent problems of extreme fragility and low sensitivity. Clearly a need exists for an apparatus which can make practical advantage of the mutual coupling probe principle for nondestructively testing multilayer board plated-through holes for critical structural defects.

A unique mutual coupling apparatus which employs high permeability magnetic flux paths for the tip of the probe which is to be inserted in multilayer board plated-through holes was proposed in response to NASA RFP 1-0-60-00083. The key to the new approach is that the magnetic flux for mutual coupling would be directed to and from the probe tip by magnetic circuitry rather than by miniature electrical coils. By this means, a simpler, much more sensitive and very rugged device could result.

The new apparatus is called a magnetic circuitry mutual coupling probe device. It could consist of one or more pairs of magnetic circuits which extend from the probe tip, which is of a diameter small enough to be inserted into the plated-through holes to be tested, to the probe body, which remains outside the holes and can be much larger in size. At the probe tip, the two legs of each magnetic circuit would terminate at pole faces. The external magnetic fluxes for mutual coupling are formed in the air gap between the pole faces. In the probe body, each magnetic circuit is wound with an excitation or sensor coil which creates the interface with conventional accessory instrumentation.

The development, design, fabrication, and testing of mutual coupling probes based on the magnetic circuitry concept were authorized by NASA Contract NAS8-25704. The effort expended on that contract and the results obtained are compiled within this report.

The technical contributions of L. J. Johnson and J. Farrar during the inception of this program and of K. K. Jin during the design, fabrication, and testing phases are gratefully acknowledged. R. A. Saviola and A. Strusinskas contributed their skills to all mechanical aspects of probe fabrication. The efforts of H. V. Connelly on plating the probes and on fabrication of the test multilayer boards were exceptional. L. H. Seymour contributed significantly during final functional evaluation of the probes and analysis of the resulting data.

## STATE-OF-THE-ART SURVEY

A search was conducted for existing instrumentation or techniques which prove capable of detecting poor electrical properties in plated-through-holes and in connecting circuitry at the junctions of plated-through-holes without destroying the specimens under test.

## Testing Techniques

The following list of nondestructive testing techniques can be used to evaluate materials of the types that are found in multilayer printed circuit boards:

(1) Mutual coupling of magnetic fields
(2) Magnetic field injection
(3) Magnetic particles
(4) Charged particles
(5) Thermoelectric
(6) Infrared
(7) Eddy current
(8) Electric current
(9) Dielectric
(10) Electrostatic
(11) Radiography, X ray
(12) Laminography, X ray
(13) Beta ray
(14) Microwave
(15) Sonic
(16) Acoustic Impact
(17) Dynamic resistance

Some of the techniques listed above have been developed to the point that commercial instruments are available for use, others are still limited to elaborate and costly laboratory-type setups.

The following brief descriptions discuss how the more pertinent techniques work and the prime sources of currently available instrumentation for each:

(1) Magnetic Particle Inspection (Available from Magnaflux Corp.)

Magnetic particle inspection is the introduction of a magnetic force field in ferromagnetic material which results in local flux leakage at irregularities or discontinuities. Application of powdered magnetic material localizes at the flux leakage areas delineating discontinuities for evaluation. The magnetic particle inspection technique is not easily adaptable to plated-through-hole inspection.

(2) Infrared Inspection (Available from Autonetics)

Infrared inspection applications usually detect electromagnetic radiation emitted by heat in the light spectrum infrared region given off by identical multilayer boards under similar operating conditions. The detector uses a refractive optical system to detect temperature variations/unit area/deg. This technique has been reduced to practice by Autonetics, but is rather expensive and complex.

(3) Eddy Current Inspection Technique (Available from Unit Process Assemblies Corp.)

When an alternating current is passed through a coil of wire, a magnetic field is created in the vicinity of the current.

If the coil is placed in proximity to a metal conductor, the magnetic flux induces eddy currents in the surface region. A change in flow of the eddy currents caused by surface cracks or coatings alters the voltage across the coil. The slight changes in voltage can be detected by a meter and provide useful information about the material being tested. This inspection technique has been used in the inspection of printed circuit boards. However, the technique is not readily adaptable to plated-through-hole inspection.

(4) Radiography, X-Ray Laminography (Available from Autonetics)

The laminography X-ray process has been developed to the point of a useful, practical inspection technique by Autonetics. The apparatus has been used by Autonetics multilayer board inspection personnel. However, the total determination of plated-through-holes integrity by this method requires many photographs, and therefore is expensive and time consuming. Also, the resolution is insufficient to determine all plated-through-hole defect types.

(5) Radiation Backscatter (Available from Unit Process Assemblies, Inc.)

If high-speed electrons (beta rays) impinge on a material, some rays are reflected and the intensity of the reflected rays depends upon the atomic number (or density) of the reflecting substance; the greater the density, the greater the percentage of reflected radiation. This principle permits the measurement of thin layers of metal-on-insulation, as in printed circuits, and has recently been adapted to plated-through-hole measurements.

(6) Mutual Coupling Technique

The mutual coupling technique uses two magnetic circuits arranged so that minimum coupling between the flux paths of the two circuits exist in a homogenous reluctance media. One of the two circuits is used as an excitation source and the other is used for sensing flux which is spatially distorted from the pattern generated in a uniform media. The amount and the polarity of the sensed flux is measured on a coil coupled to the sensing flux path. The variations and magnitudes can be related to the characteristics of the areas being measured or inspected. The mutual coupling technique was originated and experimentally proven by the Illinois Institute of Technology on NASA Contract NAS8-11288 and is the technique chosen for development of a practical instrument on this present contract. The literature and vendor search to date has not revealed the existence of anv available instrument for measuring plated-through holes by this or a similar technique.

## Available Instruments

Some commercial instruments are available which specifically claim to be capable of measuring plated-through-hole defects defects. Representative examples are described below:

(1) Caviderm Instrument (Unit Process Assemblies Company)

This instrument detects plated-through-hole imperfections such as cracks, voids, insufficient plating, bath contaminants, and porosity. The instrument is capable of measuring plated-through-holes as small as 0.010 in. ID. The unit is self-calibrating and requires no reference standards. The principle of operation employs an accurate resistivity measuring technique by the dc resistance-checking method. The detection of defects is deduced from deviations in the resistance of defective holes from the resistance of a fully acceptable hole of the size and type desired. The original principle was developed and reported by the Sandia Corporation.

(2) Microderm Instrument (Unit Process Assemblies Company)

The Microderm instrument, Model TH-1, measures the copper thickness in plated-through-holes, nondestructively. The manufacturer claims that no special sample preparation is required and the instrument will measure the copper thickness in the plated-through-hole ranging from 0.0005 to 0.003 in. thick. The minimum hole size measurable is limited to 0.034 in. diameter and a depth of 0.063 in. The principle of operation is Beta backscatter and a strontium isotope is used for the radiation source.

(3) Permascope Instrument (Twin City Testing Corporation)

The Permascope instrument is a film thickness testing instrument that can test the thickness of films inside holes. The instrument is limited to a minimum inside diameter of 0.9375 in. and therefore is not practical for printed circuit plated-through-hole measurements. The Permascope principle of operation requires a magnetic substrate which is not generally found in printed circuits and therefore is not a very suitable principle, even if the probe were capable of entering small holes.

## Recent Patents

A U.S. Patent Office disclosure resulting in the issuance of U.S. Pat. No. 3,495,166 entitled "Eddy Current Crack Detection System using Crossed Coils," was found in the current literature search. This invention was patented February 10, 1970 by Donald E. Lorenzi, Hamilton Migel, and Donald T. O'Connor and assigned to the Magnaflux Corporation. The principle of operation is similar to the mutual coupling technique employed on NASA Contract NAS8-11288 which is the prior work which the program reported herein used as a technical achievement baseline. At the present time, the Magnaflux Corporation does not have an instrument developed for the measurement (nondestructive) of poor electrical or structural characteristics in printed circuit plated-through holes.

### Other Techniques

The general literature search revealed many techniques which could conceivably be used for nondestructive testing of plated-through-holes. The techniques are merely listed here since no applicable equipment could be found using the techniques for the specific purpose of the present effort.

(1) Optical diffraction

(2) Sonic holography

(3) Electrical nonlinearity testing

(4) Ultraviolet inspection

(5) Neutron radiography

(6) Liquid crystal refraction

## THEORETICAL CONSIDERATIONS

A mutual coupling probe for the detection of defects in plated-through-holes of multilayer printed circuit boards uses an excitation circuit and a sensor circuit. The high-frequency excitation circuit produces a magnetic flux which links with the hole wall material. Voltages are induced in the hole wall plating by this flux and the currents cirulate in paths determined by the geometry of the conducting material in the area. The adjacent sensor circuit output is proportional to that part of the flux produced by the circulating currents which link with its circuits.

The original mutual coupling probe concept studied on NASA Contract NAS8-11288, used small coils in a figure "8" configuration for the excitation and sensor circuits. Figure 1 shows the coil arrangement and the probe operation to detect a gap defect bewteen the plated-through wall and an internal conductor pad. Part of the excitation flux links with the conductive loop formed around the gap and causes a current to circulate in this loop. A portion of the flux produced by this current links with the sensor coil and generates the output voltage.

This method of inserting the probe body containing the excitation coil, pickup coil, and shielding into the hole for measurements, places severe restrictions on the coil size. As a result, only low excitation levels and very low sensor coil output voltages are possible. The experimental probes of

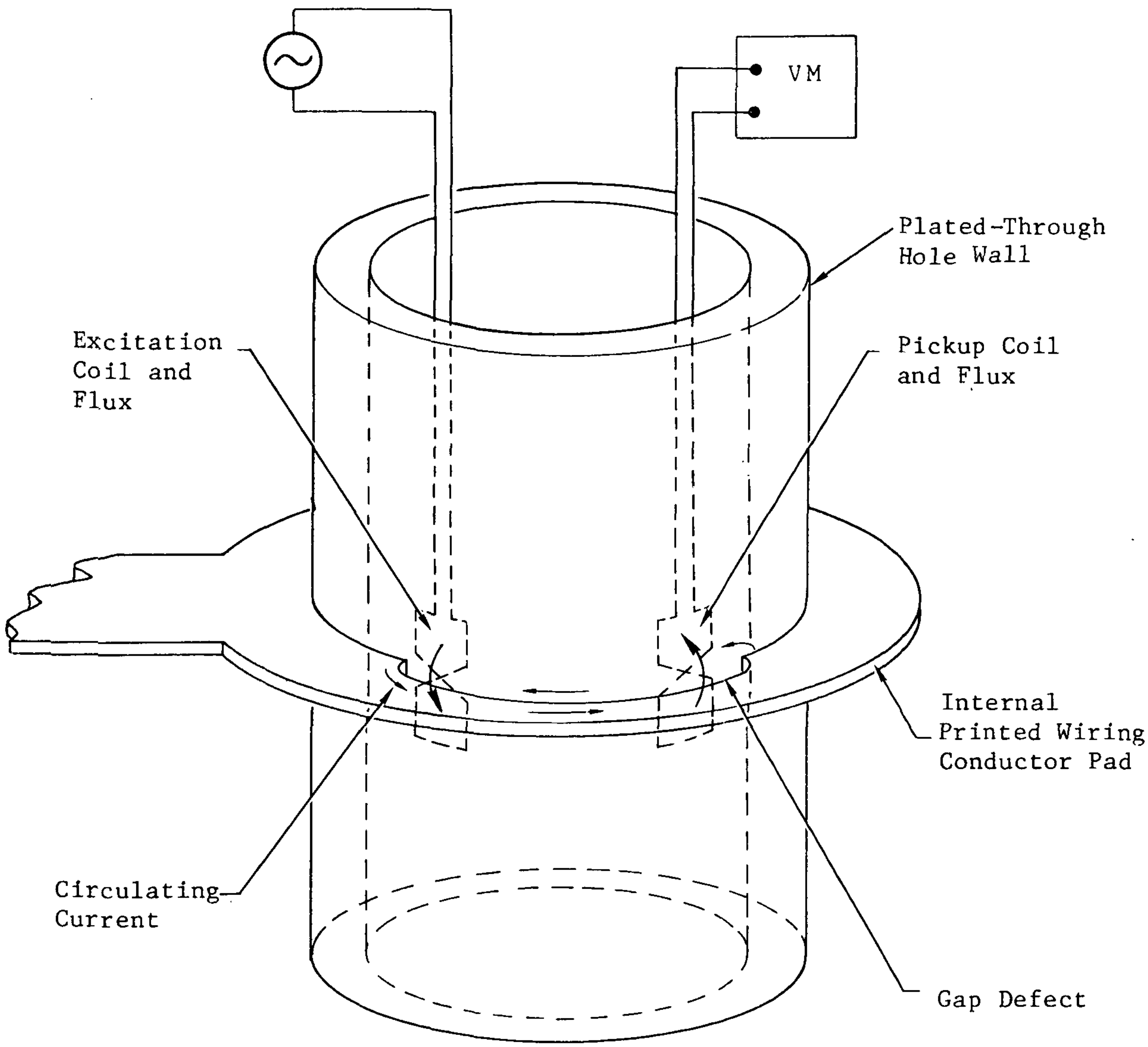


Figure 1. Operational Principle of a Figure "8" Coil Mutual Coupling Probe

this type, developed on NASA Contract NAS8-11288, were as small as 0.020 in. in diameter, but the sensor output coupling voltage was only about 1 μv. Practical use of the mutual probe concept would require increased sensitivity with much higher output signals.

To achieve improved performance, a new design was proposed which uses separate excitation and sensor magnetic flux paths for that part of the probe which is inserted in the multilayer printed circuit board holes. High permeability ferrite material is used to contain and direct the magnetic flux in the excitation and sensor circuits. The excitation and sensor coils are an extended assembly outside the hole. By placing the excitation and sensor coils outside the hole, larger coils can be used to increase the excitation level and the sensor output signal into the millivolt range.

The relative sensitivities of the two design concepts are compared. The inserted figure "8" coil probe has four turns in each coil. The magnetic circuitry probe can easily accomodate 100 turns or more in each circuit. For the same excitation current in each probe, this increase of turns by a factor of 25 in the excitation and sensor coils will increase the probe sensitivity by the factor squared, or 625 times. In addition, the presence of magnetic materials in the probe working area reduces by about one-half the length of flux paths in air for another factor of approximately two. Use of the magnetic circuitry probe concept thus, in principle, increases the probe sensitivity more than 1000 times.

Figure 2 shows the magnetic circuitry arrangement, the internal and external shielding, and the configuration in the probe working area. In the inserted part of the probe, an air gap in each magnetic circuit is used to provide discrete areas for the excitation flux and for the sensor circuit. Each of the circuits can be separately shielded to effectively control the direct coupling. Except for the increased output signal level, the magnetic circuitry probe operation is basically the same as the figure "8" coil. Both probe concepts are inherently very sensitive to changes in the radial clearance between the hole wall and the probe body. This normally requires that the probe be in firm contact with the hole wall during use.

## PROOF-OF-PRINCIPLE EXPERIMENTS

Some preliminary experiments were performed to demonstrate the mutual coupling principle of operation in the detection of simulated printed circuit board defects. Simplified versions of both the figure "8" coil probe concept from NASA Contract NAS8-11288 and the proposed magnetic circuit probe concept for this study (Autonetics Proposal T70-83/501) were used to demonstrate the mutual coupling concept.

Experiments were made using flat brass sheets and two figure "8" coils dimensioned and arranged as shown in Figure 3. A plated-through-hole separation or gap defect was simulated by the copper wire soldered to the brass plate

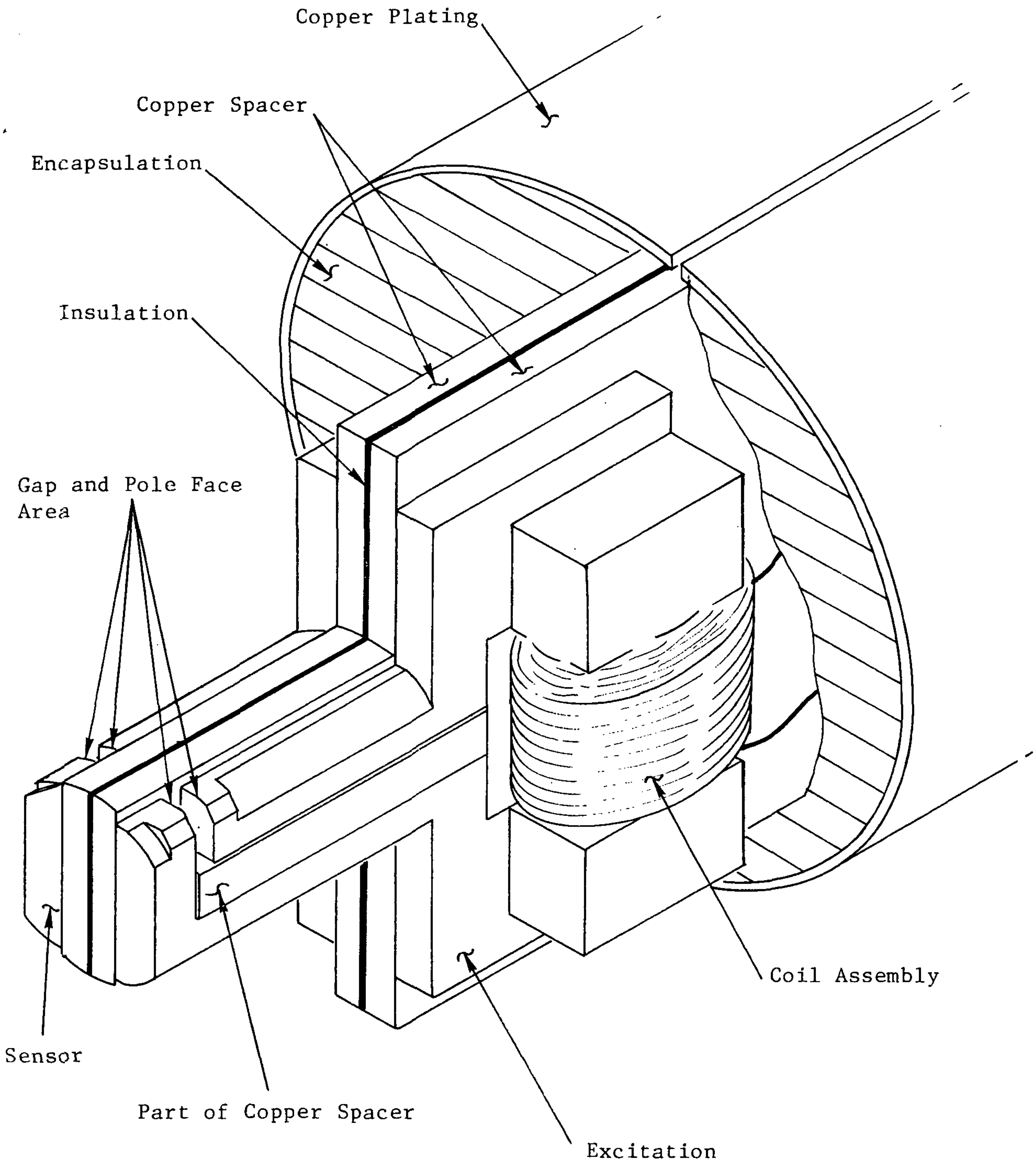


Figure 2. Configuration of a Magnetic Circuitry Mutual Coupling Probe

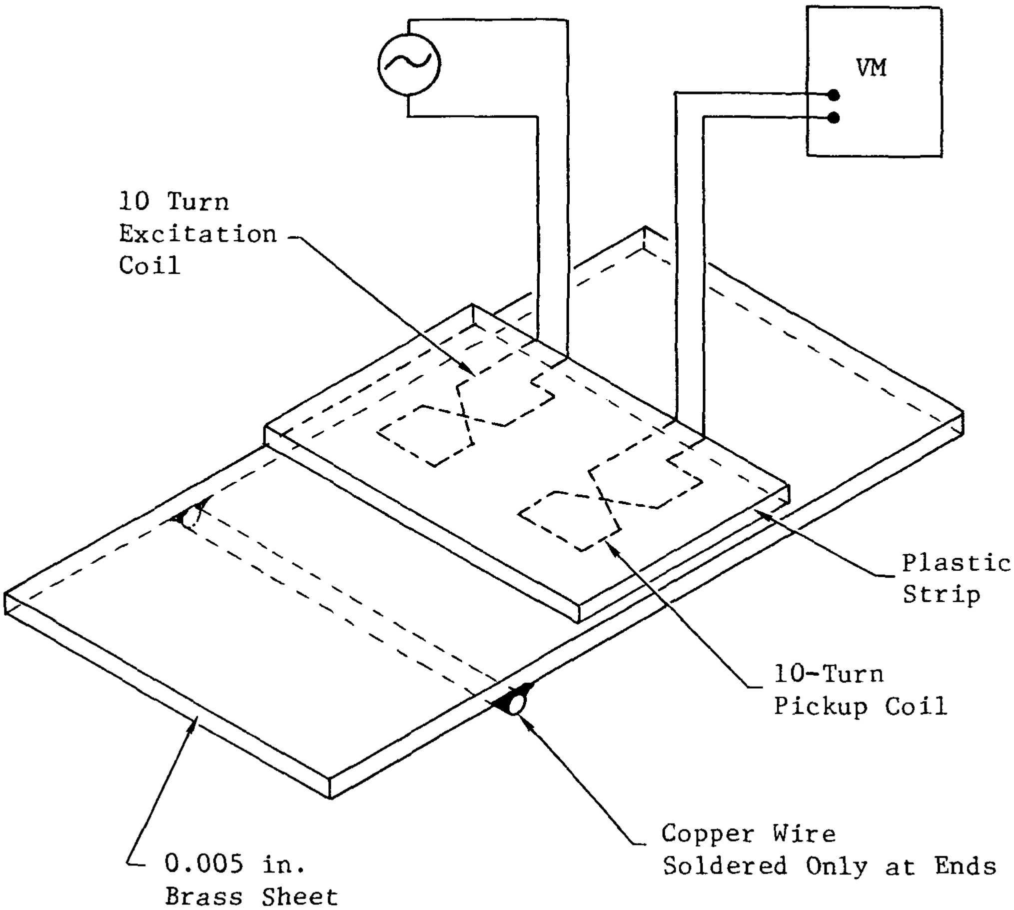


Figure 3. Experimental Check of Mutual Coupling Principle with Figure "8" Coils

at the ends, only. Measurements were made with an excitation coil current of 180 ma at a frequency of 20 kHz. The direct coupling of this unshielded coil arrangement was 0.16 mv. Table I shows the results obtained with a brass plate 0.005 in. thick. The data show a definite change in the sensor output signal for the gap defect and for the brass plate, only. However, the ratio of gap defect voltage to wall voltage of 1.36 is considerably lower than the ratios reported on NASA Contract NAS8-11288.

TABLE I
RESULTS OF PROOF-OF-PRINCIPLE EXPERIMENTS WITH SIMULATED FIGURE "8" AND MAGNETIC CIRCUITRY MUTUAL COUPLING DEVICES

| | Pickup Coupling (mv) | | |
|---|---|---|---|
| Probe Type | Plate Only | Gap Detect | Ratio Gap/Plate |
| Figure "8" Coils | 0.58 | 0.79 | 1.36 |
| Ferrite "C" Cores | 5.8 | 6.5 | 1.12 |

Table I also shows the results of measurements using two small ferrite "C" cores instead of the figure "8" coils. Each core has a four-turn coil dimensioned and arranged as shown in Figure 4. Measurements were made with an excitation coil current of 500 ma at a frequency of 40 kHz. The direct coupling of the unshielded "C" core coil arrangement was 4 mv. The sensor output signal was higher by about an order of magnitude, compared to the figure "8" coil measurements. Again, the ratio of the gap defect voltage to the wall voltage of 1.12 is relatively low.

Both of these experimental devices had a high amount of direct coupling, and the configurations made them difficult to shield properly. This condition contributed to the low ratios obtained. A 10-times size experimental ferrite probe, shown in Figure 5, was made which had magnetic circuits and copper support (and internal shielding) structures that more closely duplicated the proposed magnetic circuit probe. Flat sheets of brass or copper were used to check probe operation, and several experimental shielding materials and methods were tried. The first test dealt with the optimum configuration for the copper spacer between the ferrite pieces making up the four links of the excitation and sensor circuits along the probe body. The key question was whether the copper spacer could be of one continuous piece as suggested in the original proposal, or whether certain refinements would be needed to reduce the direct pickup. Measurements with the experimental probe clearly demonstrated a substantial reduction in direct pickup when the internal copper structures of the sensor circuit and the excitation circuit are separate, i.e., electrically insulated from each other.

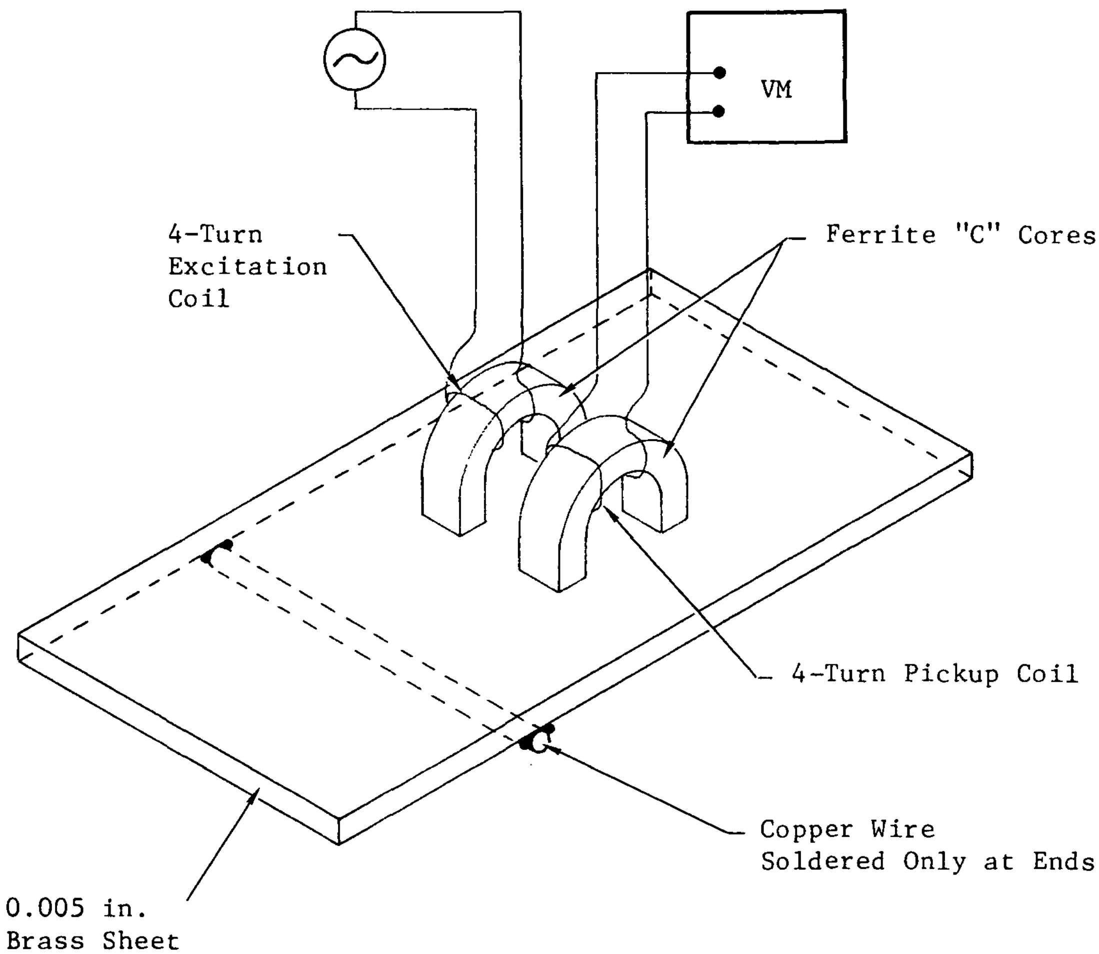


Figure 4. Experimental Check of Mutual Coupling Principle with Ferrite Magnetic Circuits

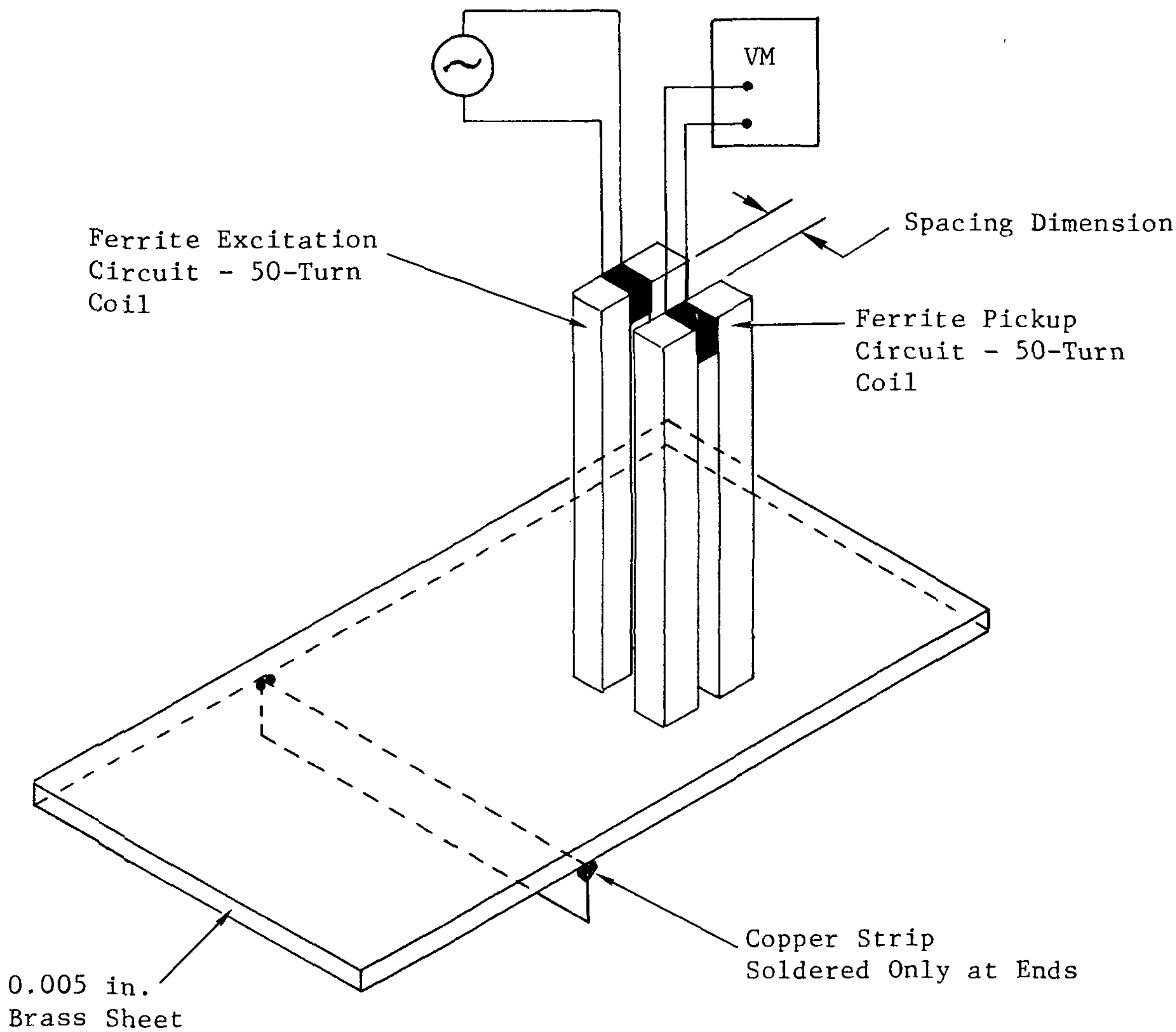


Figure 5. Experimental Check of Mutual Coupling Principle with a 10-Times Size Ferrite Magnetic Circuit

Both magnetic and nonmagnetic shielding materials were evaluated to reduce the direct pickup along the ferrite path length. The magnetic shielding material used was 0.004 in. Mumetal foil. The nonmagnetic material was 0.001 in. copper foil. An assessment of the effect of wrapping layers of the shielding foil around the length of the sensor body showed a substantial decrease in the direct pickup. Direct pickup measurements made over an excitation frequency range from 50 to 700 kHz showed that both magnetic and nonmagnetic shielding materials were effective in reducing pickup. The magnetic material (Mumetal) was most effective at the lower excitation frequencies and the nonmagnetic material (copper) was most effective at the higher excitation frequencies. Copper material was chosen for the shielding in the final probe design since the probes were expected to operate at the higher excitation frequencies, and also because copper material could be more readily plated onto the required surfaces.

All effort with this experimental probe indicated that control of the direct pickup at the working end of the probe could be accomplished by increasing the spacing between the sensor and excitation assemblies. The proposed probe design should have adequate spacing with its internal copper structure and cylindrical configuration to hold the direct pickup in this area to an acceptable level. Table II shows the test results obtained with the experimental probe with changes in the spacing between the sensor and excitation assemblies. The sensor shielding was a combination of copper and Mumetal foil wrappings. The signal ratio of 2.3 for a gap defect is an improvement over the previous experimental probes, however, a larger signal ratio would make the probe more practical for use.

TABLE II
TEST RESULTS WITH 10-TIMES SIZE MAGNETIC PROBE

| | Spacing Between Sensor and Excitation Circuits | |
|---|---|---|
| | 0.125 in. | 0.375 in. |
| Pickup Coupling Over No Defect (mv) | 2.6 | 0.35 |
| Pickup Coupling Over Gap Defect (mv) | 3.15 | 0.80 |
| Signal Ratio $\frac{\text{Gap Defect}}{\text{No Defect}}$ | 1.20 | 2.3 |

This experimental probe demonstrates the practicality of using ferrite magnetic material to direct and contain the necessary excitation and sensor flux in the working area of the proposed probe. The methods used to control the direct pickup resulting from these experimental probes were incorporated in the 0.060 in. diameter probe that was designed and fabricated during the next phase of the probe development.

## DEVELOPMENT OF PROBE DESIGNS

### Single Probes

The final version of the 0.060 in. diameter single-probe design evolved during a series of design and fabrication changes in which the primary effort was to reduce the direct coupling to an acceptable level. Shielding for the first probe design fabricated consisted of 0.002 in. copper plating on the 0.060 in. diameter area, and used copper tubing over the larger diameter coil assembly area. As a result, direct coupling signals were unacceptably large. Experimentation with shielding changes on the probe showed that a common shield (tube) around the excitation and sensor coil assembly increased the direct coupling, yet some shielding in this area of the probe was a necessity. It was concluded that it was necessary to (1) provide separate shielding for the excitation and sensor circuits along the entire length of the probe and (2) the external shielding material for each circuit should be continuous with the internal copper shielding and spacing structure of that circuit. The two internal copper spacers were already separated by an insulating material.

This new shielding concept required molding or encapsulation of the upper coil assembly area with an insulating compound to provide a surface for copper plating. A maskant could be used along the exposed surface of the insulated dividing line between the copper spacers during the plating process. In addition to providing shielding, this process greatly increased the ruggedness and reliability of the probe assembly. The first probe was partially reworked to evaluate the efficacy of the modified design.

The second 0.060 in. diameter probe fabricated to the modified design incurred some loss of ferrite material in one of the pole faces during machining operations, but it was useful for experimental purposes. Direct coupling was reduced to an acceptable level, and is shown in Figure 6 as function of the excitation frequency. Also shown is the probe operation for a gap defect in an 0.005 in. copper sheet. This is not a true representation of a separation defect in a printed circuit plated-through hole (no wall), and was used only to check the probe response to a gap. Although the signal ratio (gap voltage divided by the no gap voltage) is low (about 1.4), the change of several millivolts is considered a significant probe characteristic.

Probe operation in multilayer printed circuit test boards with no hole defects and with built in separation or gap defects produced relatively small signal changes, and identification of these defects was not positive enough for practical use. Data obtained with this probe from a multilayer test board hole

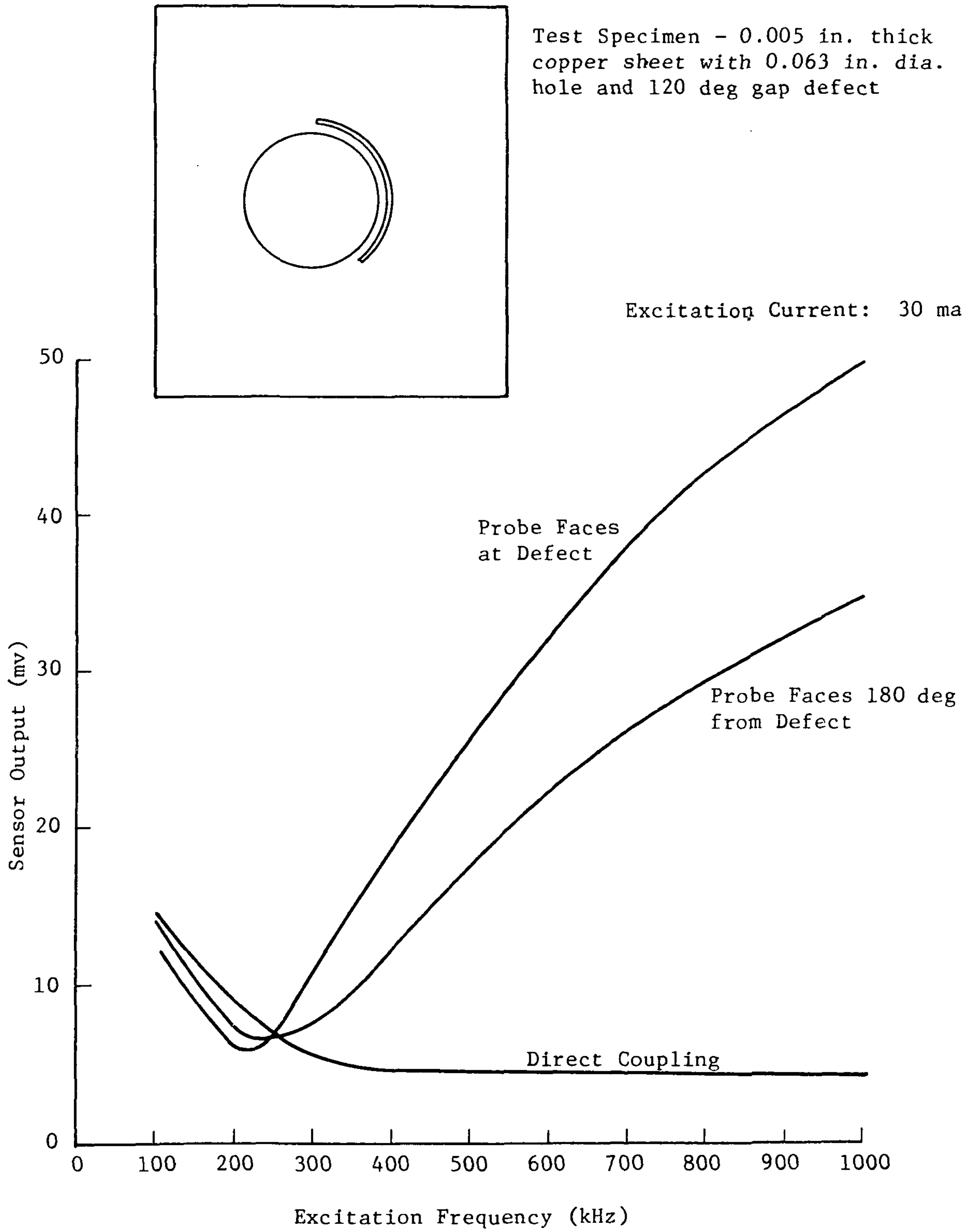


Figure 6. Response of Modified 0.060 in. Probe to Simulated Gap Defect

in which the board material and part of the hole wall were removed to visually locate the gap defect are shown in Table III.

TABLE III
RESPONSE OF 0.060 IN. SINGLE PROBE TO EXPOSED SEPARATION DEFECT IN A MULTILAYER BOARD PLATED-THROUGH HOLE

| Probe Excitation | Wall Voltage (WV) | Defect Voltage (DV) | Ratio DV/WV |
|---|---|---|---|
| Frequency: 600 kHz<br>Current: 30 ma | 18.0 mv | 22.0 mv | 1.22 |

This 4 mv defect-signal change is larger than that obtained on other holes, and is apparently due to removal of part of the hole wall. The much-larger-than-expected wall voltage of this probe makes detection of the small gap-voltage signal difficult.

Experimental determination of the effects of the copper hole wall on the flux field produced by the excitation circuit was made by measuring the voltage generated in a 1-turn search coil of 0.001 in. wire centered at the excitation pole faces, as shown in Figure 7. A comparison of the data with the search coil on a diameter formed by 0.002 in. mylar spacing and a 0.002 in copper tube shows the screening effect of the copper. This indicates that relatively small gap-defect voltages in a plated-through hole can be expected. As expected, the probe is very sensitive to radial positioning in the hole and must be held firmly against the hole wall to obtain repeatable data.

A third probe, of the same design as the second, was fabricated by a procedure requiring no machining after plating and with essentially no loss of ferrite in the pole faces. The probe direct coupling was the same as the second probe. The only apparent difference in operation was a lower wall voltage signal, about one-half the magnitude of the second probe. The reason for this difference has not been determined. This probe was used to accumulate operational data on the series of multilayer test boards made with various defects in the plated-through holes.

A 0.030 in. diameter probe was fabricated using the same ferrite circuits as the larger probe. The internal copper spacer structure was reduced proportionately in thickness. No other design and fabrication changes were made. Figure 8 shows the direct coupling of this probe. This large, direct coupling is probably the result of the decreased internal spacing between the circuits. Probe operational data were also accumulated with the 0.030 in. diameter probe on a series of multilayer test boards made with various defects in the plated-through holes.

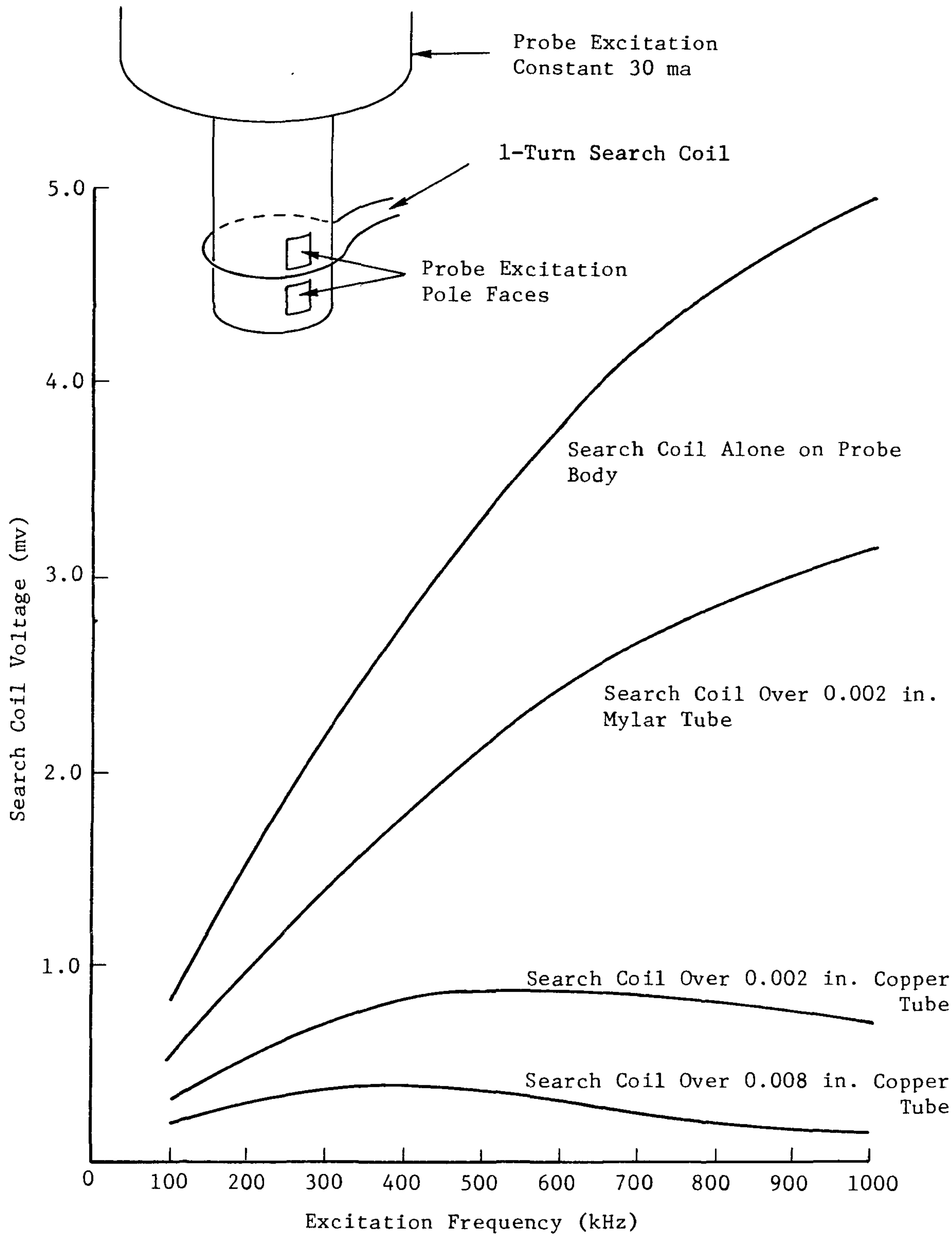


Figure 7. Penetration of Fringing Flux from Excitation Pole Faces of 0.060 in. Single Probe

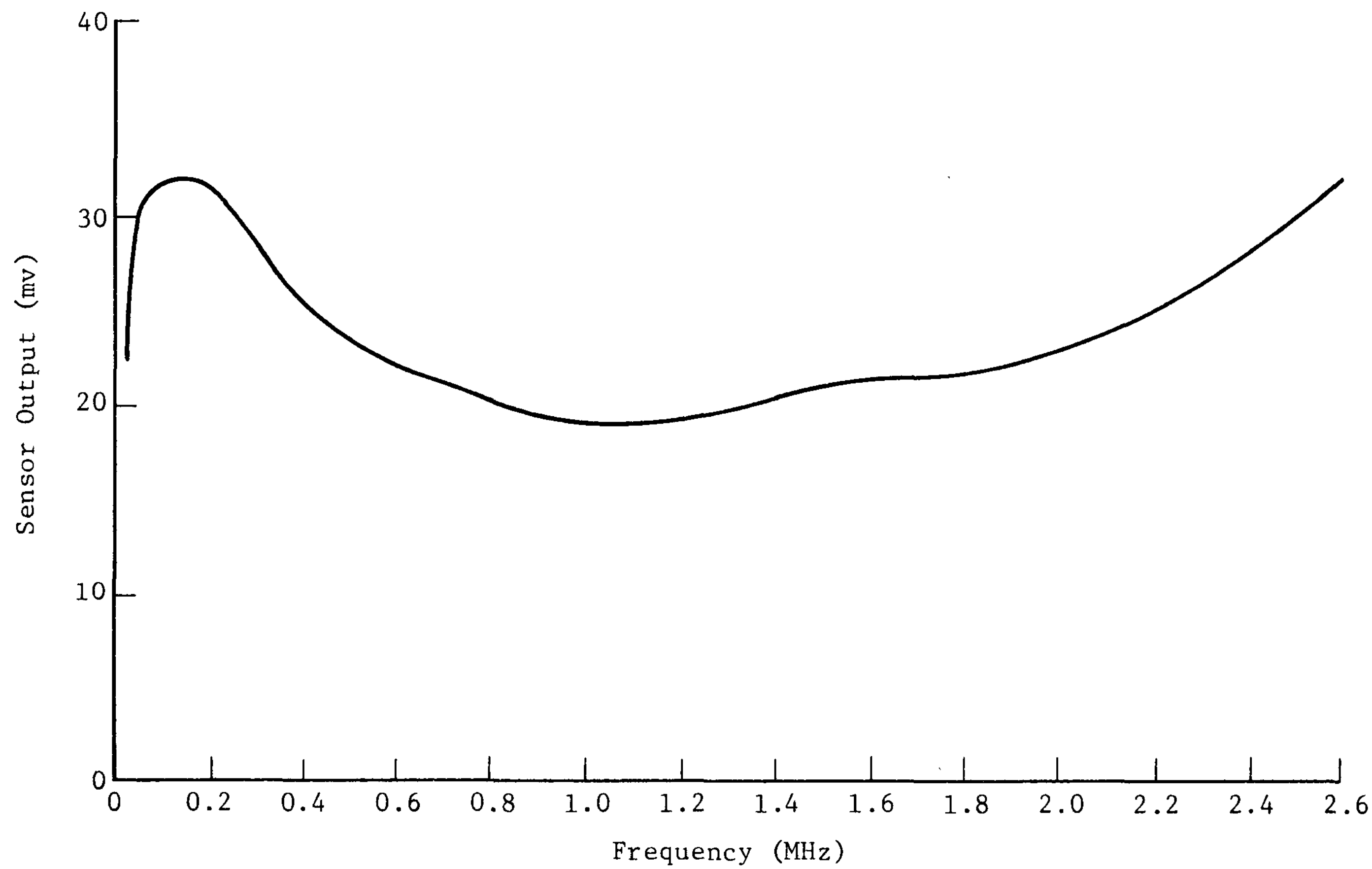


Figure 8. Direct Coupling 0.030 in. Single Probe, 20 ma Excitation

## Double Probes

All effort with the first (single) probe designs indicated the need to improve the ratio of the separation or gap defect-voltage signal to the wall-voltage signal. Since no direct way of reducing the wall signal of the magnetic circuitry probe was known, a decision was made to use a double probe design concept. The probe would operate very much like two probes simultaneously exploring diametrically-opposite areas of a hole, with a sensor output signal equal to the difference of the two generated sensor signals. Theoretically, if such a probe was centered in a hole, the sensor signal would be determined only by differences in the two hole wall areas being explored, such as defects in one area and none in the other. Practically, only a part of this effect can be realized, since centering the probe in the hole is not possible, and the device would have some built-in unbalance. The double probe design uses two sets of excitation pole faces with a common exciting coil. The sensor circuit also has two sets of pole faces and a common leg in the magnetic circuit with the pickup coil. The sensor output signal is produced by the difference in flux in the two circuits.

Figure 9 shows the magnetic circuit arrangement of the excitation and sensor sides of the double probe. The excitation circuit has two sets of pole faces with a common excitation coil and flux as shown. The sensor circuit also has two sets of pole faces and a common center leg in the magnetic circuit containing the sensor coil. With the sensor circuit flux directions as shown, the sensor output is determined by the flux flow in the common leg. When the flux in the two outside legs of the circuit is not equal, the sensor output is porportional to the inequality.

A 0.060 in. diameter double probe was fabricated with reasonable success. Some loss of ferrite in two of the pole face areas occurred and probably added to the unbalance of the magnetic circuits. However, the basic double probe design proved successful and this probe was workable. Figure 10 shows the direct coupling of this probe. Operational data were obtained with an excitation frequency of 500 kHz. This probe was used to accumulate plated-through-hole data using the same test multilayer boards as the 0.060 in. diameter single probe.

# FABRICATION OF PROBES

## Basic Fabrication Procedures

A considerable portion of the effort on this program was expended to develop and apply the fabrication procedures needed to produce the required magnetic circuitry mutual coupling probe devices. From the conception of this approach to an improved mutual-coupling probe, it was anticipated that fabrication of the magnetic circuitry devices would present a major challenge. The fabrication requirements were known to be near the present limits of conventional machine forming. The basic difficulties are inherent in the small sizes

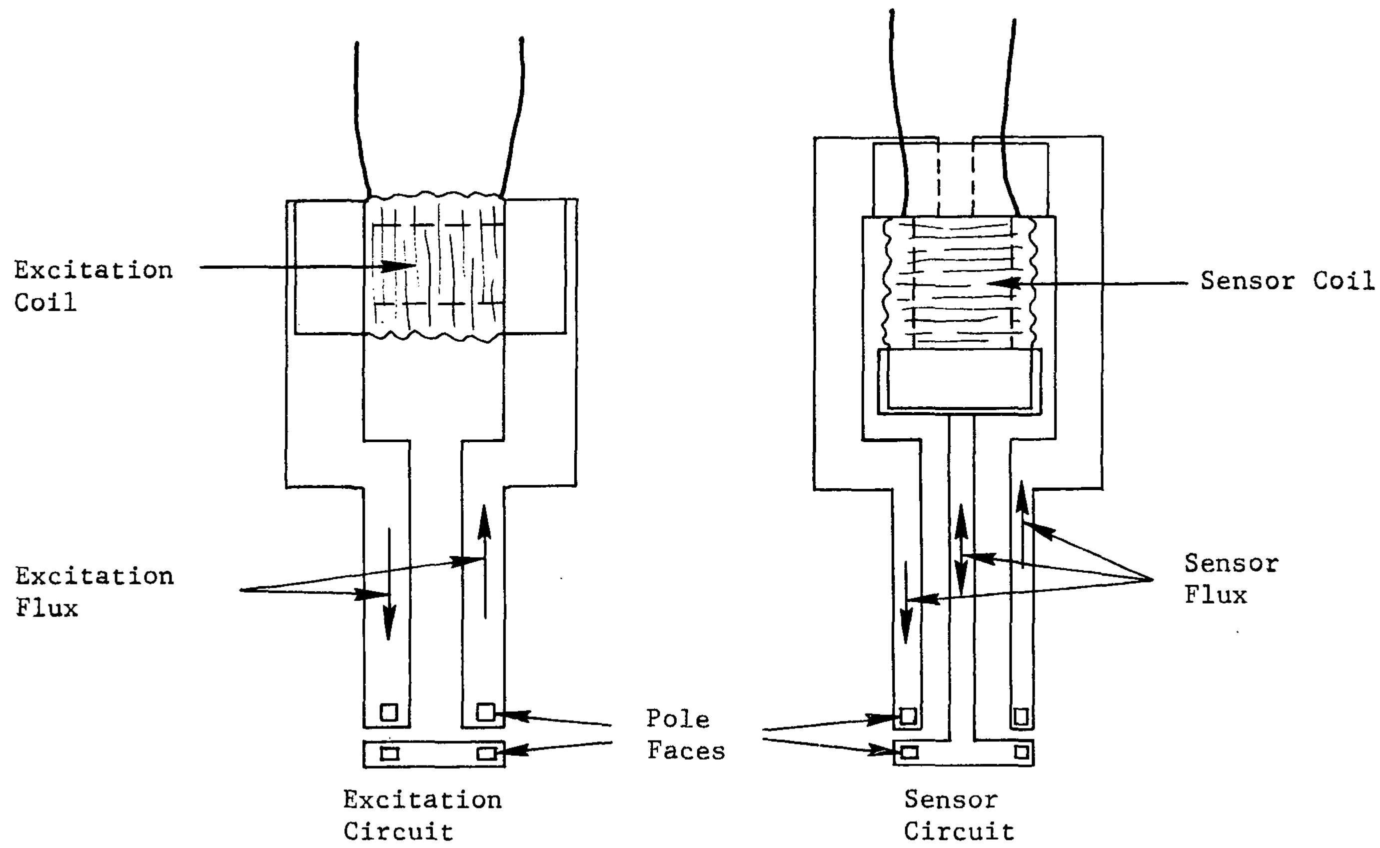


Figure 9. Mangetic Circuits of the Double Probe

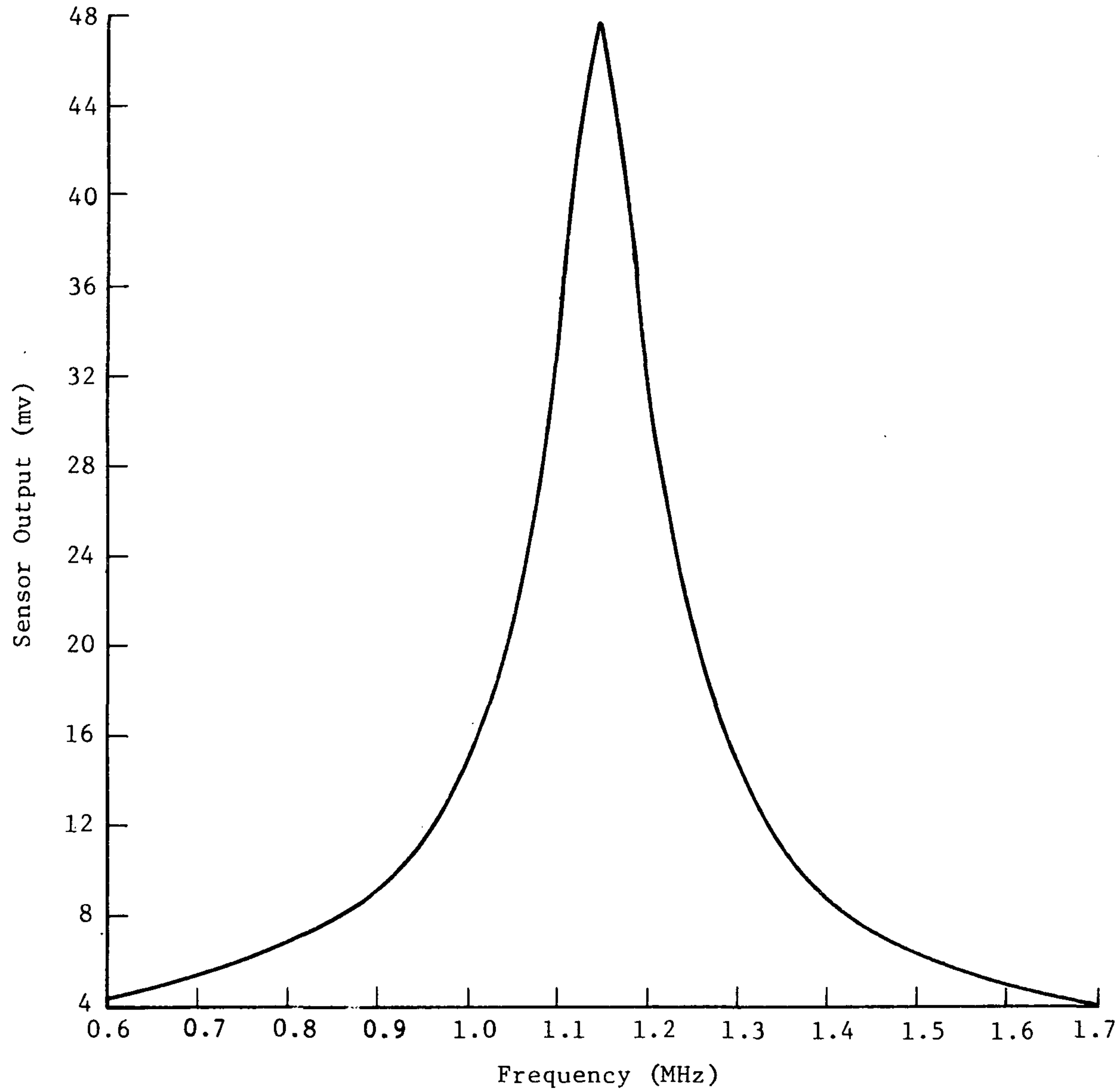


Figure 10. Direct Coupling Double Probe with 20 ma Excitation

required for probes to test typical multilayer board plated-through holes and the general configuration of the proposed design, which, although compact and rugged when completed, requires a complex and varied sequence of processing steps. Originally, it was considered feasible to employ epitaxial deposition techniques to form the small ferrite configurations additively and in place on the basic probe structure. Unfortunately, early investigation of the detail requirements for the fabrication of the necessary magnetic structures in the probe design ruled out the use of epitaxial deposition for several reasons. First, epitaxial ferrite is not directly compatible with copper because of crystal structure differences and a relatively low melting point compared with ferrite reaction deposition temperatures. Further, it did not appear that sufficient thicknesses of ferrite could be deposited epitaxially within the overall constraints of the probe fabrication scheme. Later in the program when it was necessary to introduce an even more demanding design (the double probe) the possibility of precision etching the small complex ferrite shapes was explored. It was thought that the very accurate technology of photo-resist imaging could be used to mask the ferrite for etching. However, existing technology was not suitable and no satisfactory etchants for ferrite under the required conditions are available. Some preliminary laboratory studies were conducted and one or two etchants were found which showed some slight promise. However, it soon became apparent that the extensive development work needed to obtain a satisfactory etching process for ferrite would be beyond the scope of this program.

As the design of the initial probe was developed, continuous consideration was given to the means of fabrication. Based on consultations with both machinists and process engineers, it appeared that a fabrication procedure based on machining to form the ferrite, and plating to deposit the external copper shield would be workable. This basic approach was used to fabricate the first magnetic-circuitry, mutual-coupling probe device with generally satisfactory results. Although some substantial design modifications were introduced subsequently, this same basic fabrication procedure was used for all of the probes produced for this program. Some additions to the procedure were necessary because of the design changes. Some improvements in technique evolved as additional probes were made, but the essential aspects of the machining of the ferrite pieces and the probe tip, and the plating of the external copper coating remained intact. Both the 0.60 in. diameter double probe, as well as the 0.030 in. diameter single probe, were successfully fabricated by these basic procedures. Design and functional performance limitations not withstanding, this same approach could probably be extended to fabricate a 0.020 in. tip diameter magnetic-circuitry probe. The entire basic fabrication procedure, as it applies to the design of the final series of probes produced and tested, is given in detail below.

## Fabrication of Central Copper Spacer

The central copper spacer functions both as the basic structural member upon which the magnetic-circuitry, mutual-coupling probe is assembled, and also as an internal part of the metallic shield around each magnetic circuit. Since the shields for the two magnetic circuits are to be electrically isolated, the central copper spacer design called for a sandwich-type insulation layer between two layers of copper. To fabricate the central copper spacer, two pieces of copper each with parallel opposite sides, were measured for thicknes and then bonded together. The bond line electrically isolates one copper layer from the other. Originally, bonding was accomplished with a filled-epoxy, liquid adhesive. Then, a dry-film epoxy adhesive and finally a laminated epoxy preimpregnated glass fabric B-staged (prepreg) adhesive was used. The lamination process was used for all of the later probes and provided better thickness control of the insulation layer. Also, the resulting structure was more stable to subsequent machining stresses and plating solutions. The laminated-copper, epoxy-glass sandwich was next machined to the required shape for the particular probe design to be fabricated. This machining essentially involved milling down the copper surfaces to have only the ribs of copper which would serve as a shield between the two ferrite legs of each magnetic circuit.

## Fabrication of Ferrite Shapes

Forming the various very small ferrite shapes required for the magnetic probe designs is the key to any fabrication scheme. Two machining techniques were attempted originally. One technique involved cutting and grinding the profile of each particular shape in a rod of ferrite material and then slicing off duplicate pieces to the required thickness with a diamond cutting wheel. This method produced usable ferrite shapes, but was very tedious to perform, and breakage during the slicing operation was high. The other technique employed ultrasonic impact grinding as the final machining step. This method gave very good results and was used to produce the ferrite pieces for all of the probes fabricated on this program.

To employ the ultrasonic impact grinding approach, it was first necessary to fabricate the appropriate tools. This was accomplished by first preparing, by conventional mechanical machining, Electric Discharge Machining (EDM) tools with the cross-sectional shape of each required ferrite piece. The sets of such EDM tools for the single-probe and the double-probe ferrite shapes are shown in Figures 11 and 12, respectively. Then, the EDM tools were used to sink the ferrite shapes in the ends of steel rods to form the tools for ultrasonic impact grinding. The sets of finished ultrasonic impact grinding tools for the single-probe and double-probe ferrite shapes are shown in Figures 13 and 14, respectively. With the necessary tools prepared, pieces of the ferrite material were bonded to steel blocks and machined. They were then lapped down mechanically to slabs of the thickness required for each ferrite piece. Then, by cutting through the ferrite slabs with the ultrasonic impact grinding tools, the finished ferrite shapes were formed. The ferrite shapes were removed from the steel blocks by dissolving away the bonding material. By this means, ferrite shapes of good quality and required dimensions were fabricated with high efficiency, once the tools had been made. Since the ultrasonic impact grinding put minimal mechanical stress on the final small ferrite shapes, the breakage was very low. Some of the individual ferrite pieces for single-probe and double-probe designs are shown in Figures 15 and 16, respectively. The ferrite pieces for all of the probes were fabricated from Ferroxcube 3C5 material.

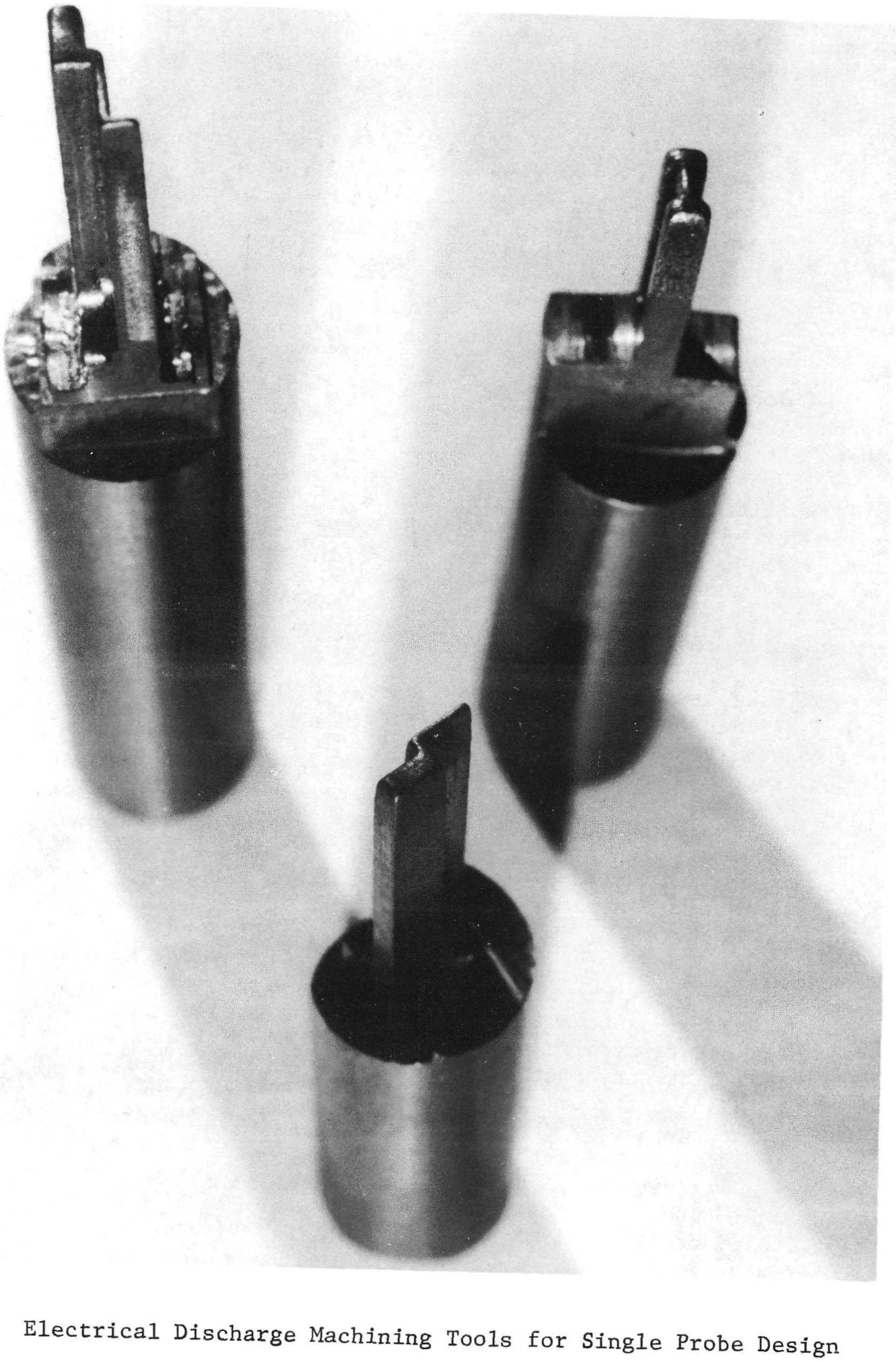

Figure 11. Electrical Discharge Machining Tools for Single Probe Design

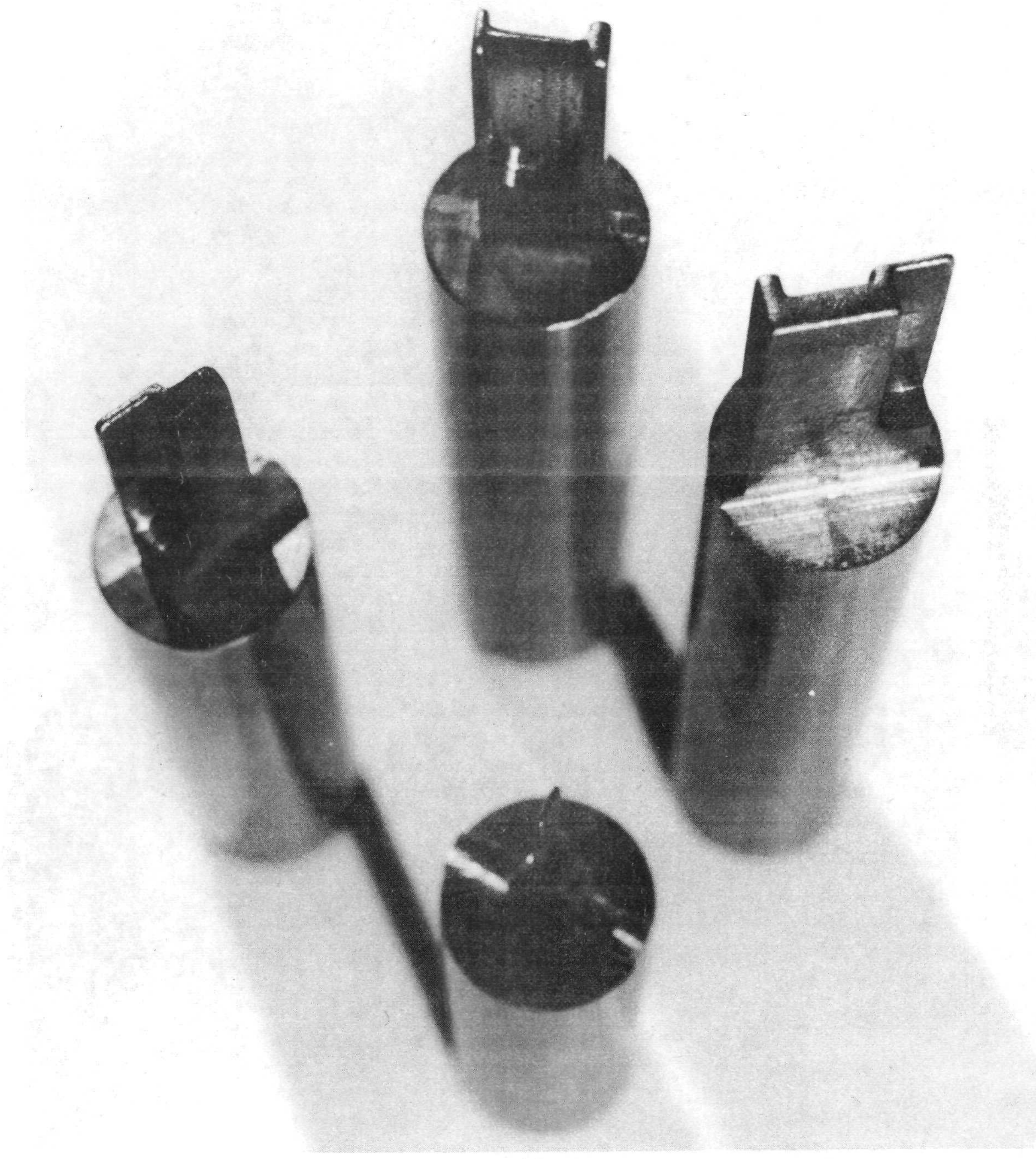

Figure 12. Electrical Discharge Machining Tools for Double Probe Design

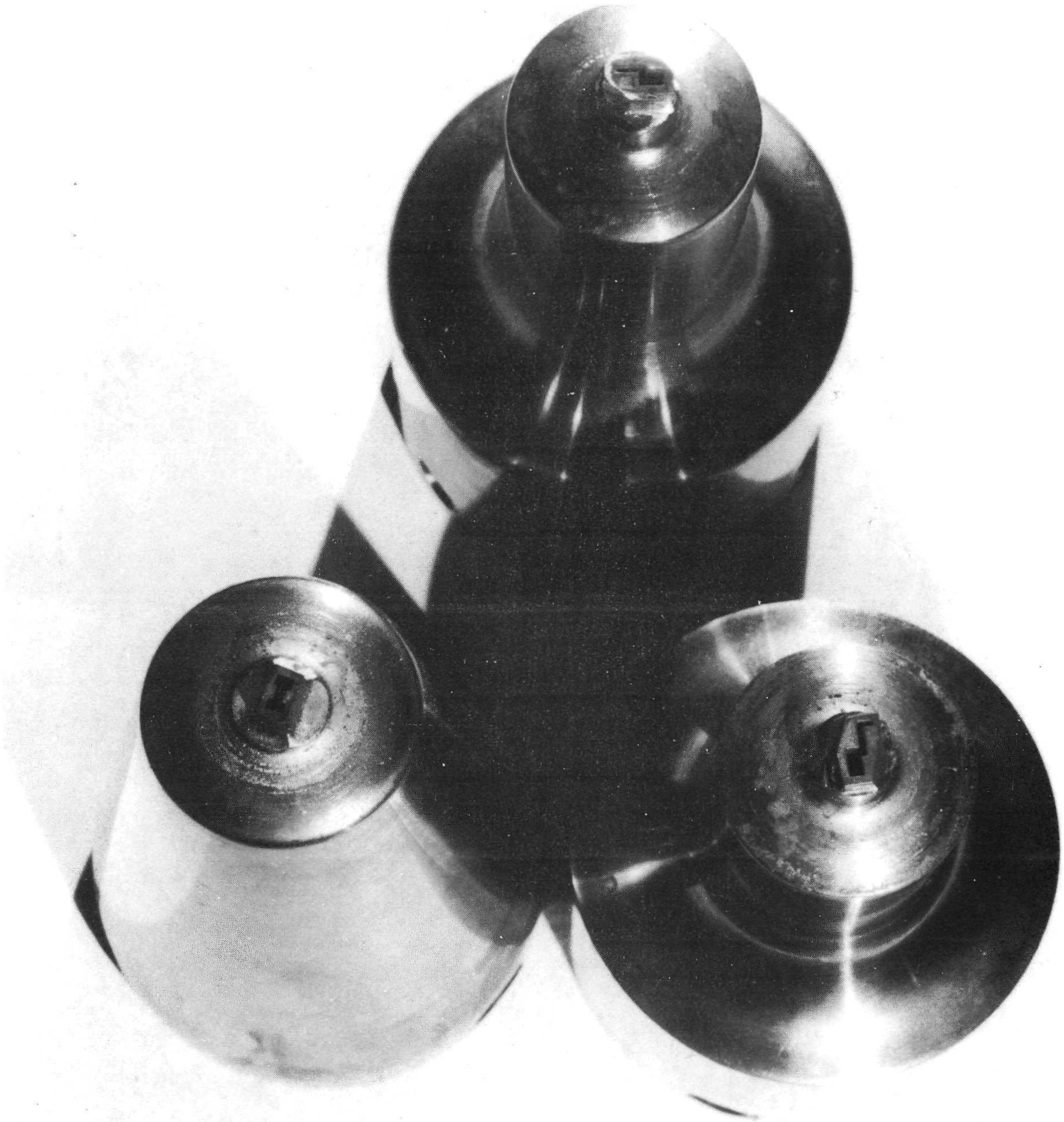

Figure 13. Ultrasonic Impact Grinding Tools for Single Probe Design

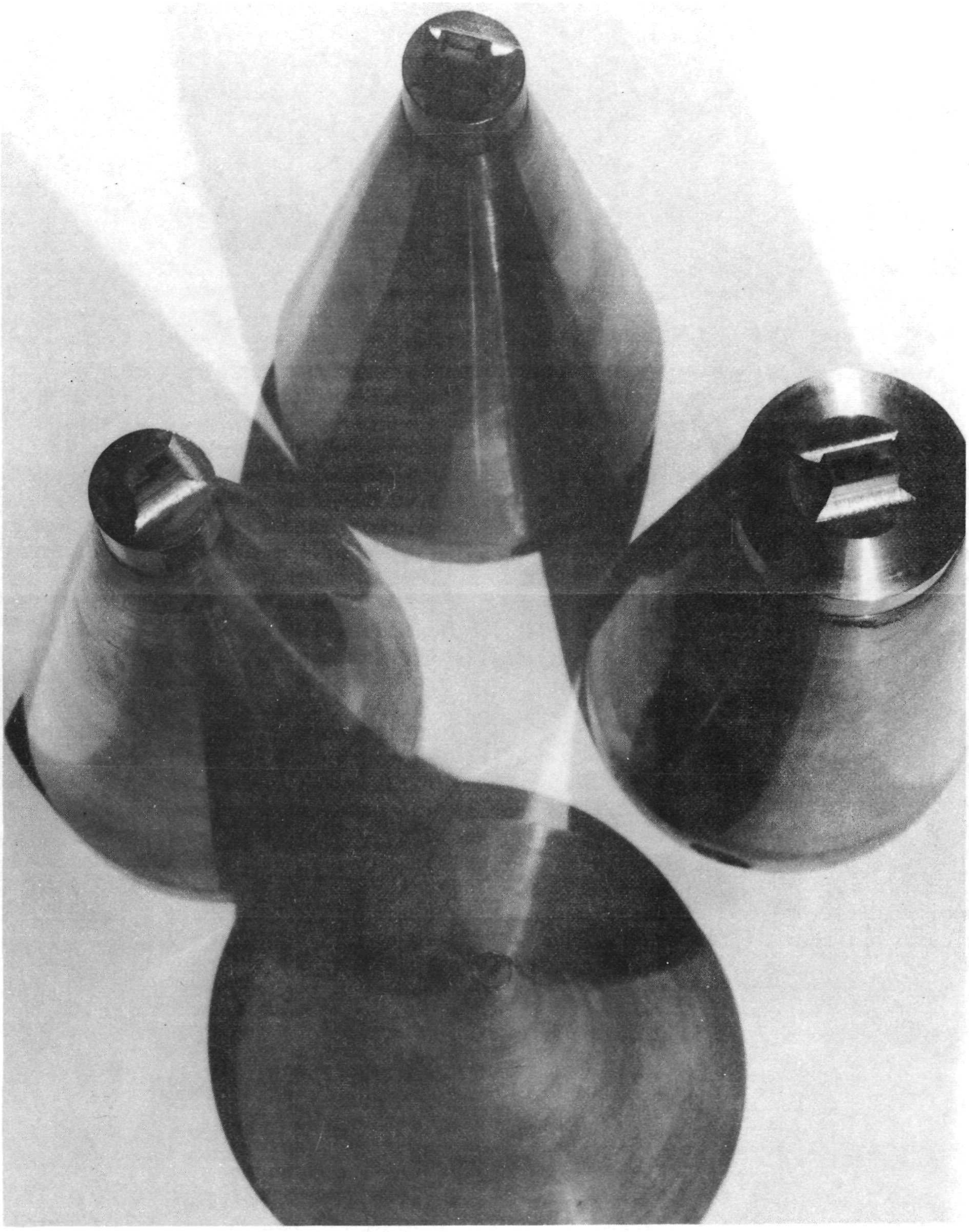

Figure 14. Ultrasonic Impact Grinding Tools for Double Probe Design

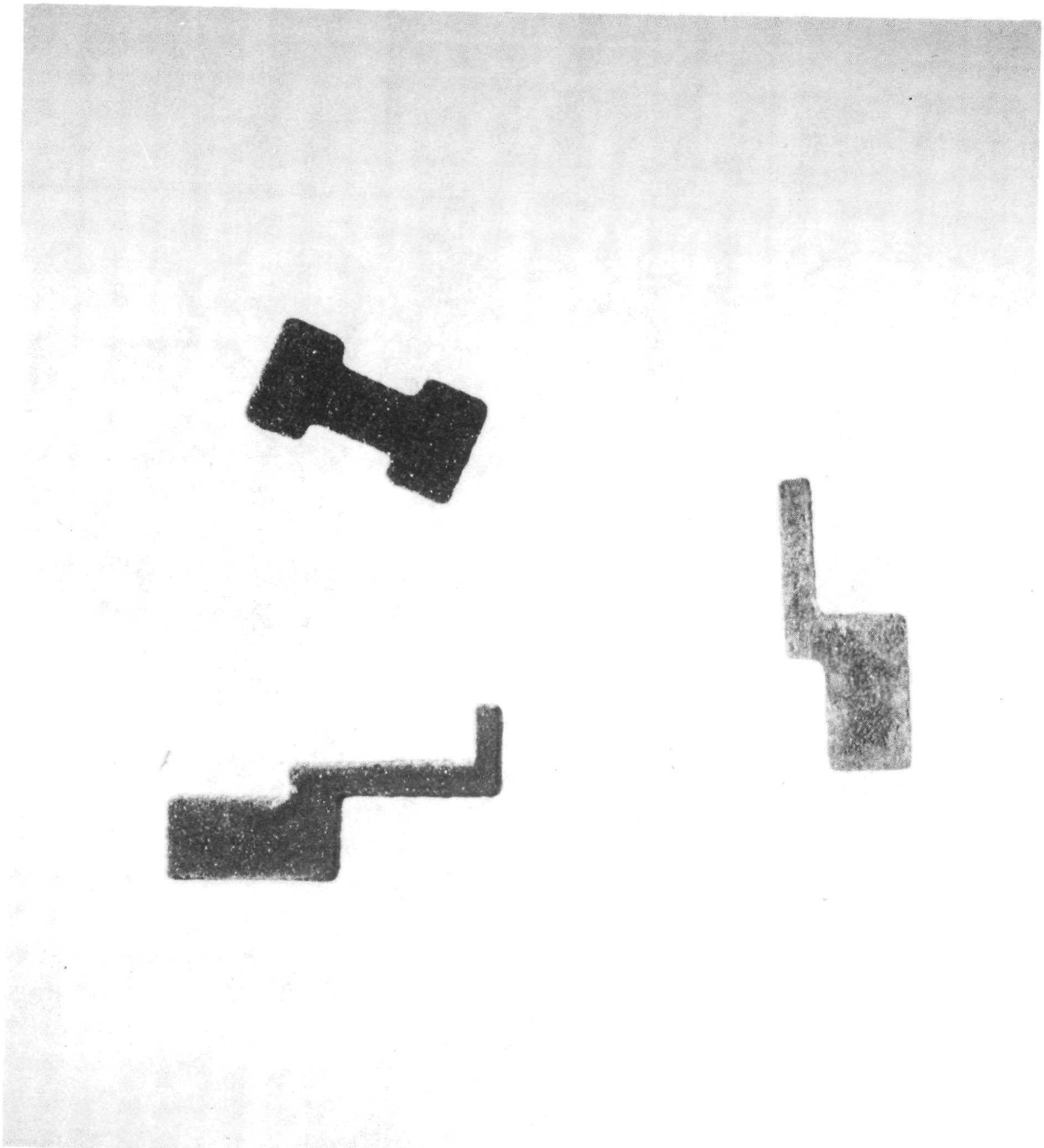

Figure 15. Individual Ferrite Pieces for Single Probe Design (10 Times Size)

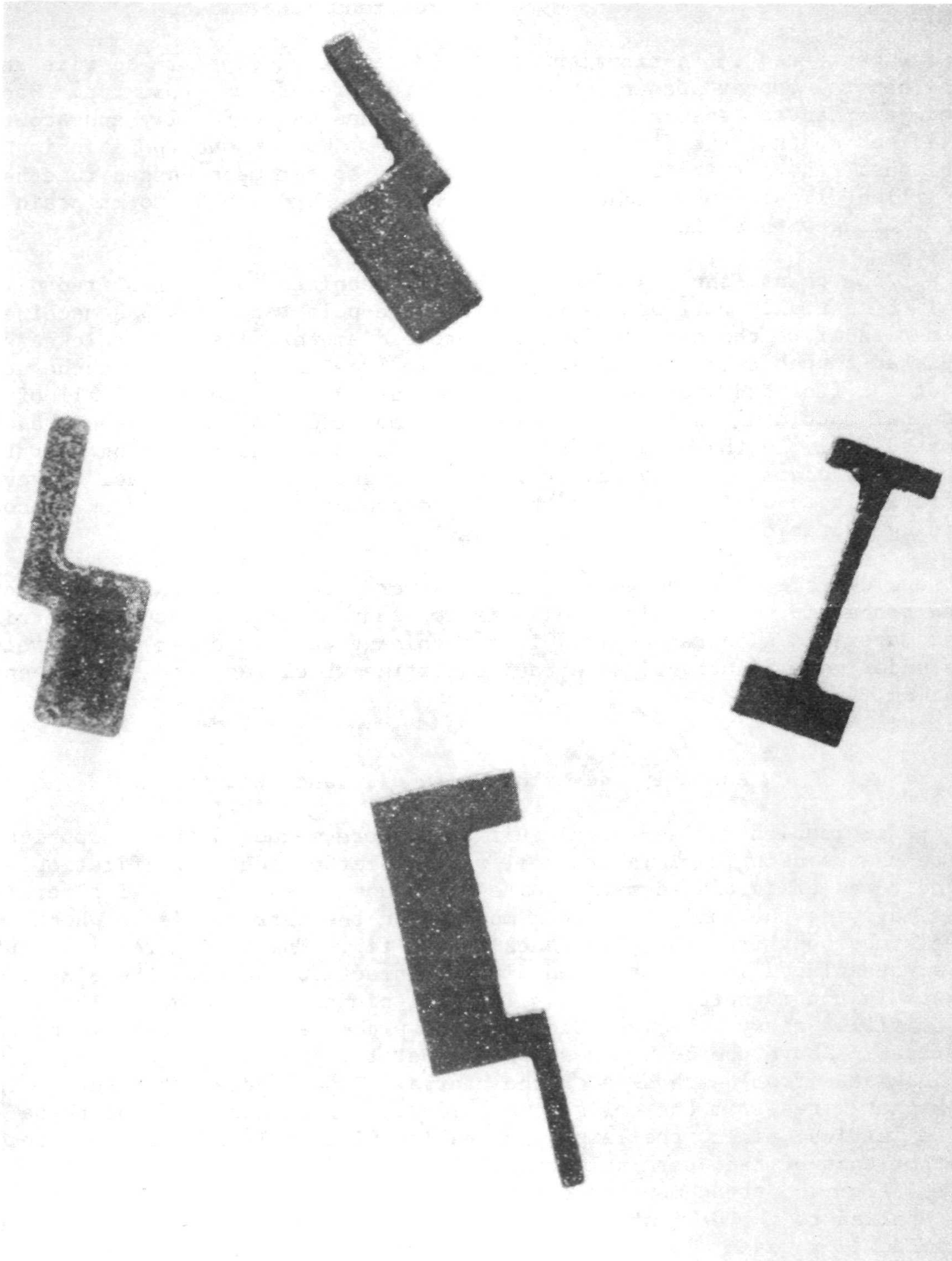

Figure 16. Individual Ferrite Pieces for Double Probe Design (10 Times Size)

## Assembly and Machining of the Probe Tip

The next step in fabrication was to mount the appropriate ferrite shapes on the central copper spacer to form the structure of the probe tip. Machining of both the central spacer and the ferrite pieces was carefully and accurately carried out so that the fit was close and even. Once proper positioning was established, the ferrite pieces and the copper spacer were bonded together with an unfilled, liquid-epoxy adhesive (Epon 282 and Hardener D) to maintain a close fitting with a minimal bond-line thickness.

At this point, the tip of the probe was machined to the required dimensions. Essentially, all of the tip except the pole face area was machined to a diameter equal to the desired finished probe diameter, less the thickness of the plated-copper external shield. The pole face area was left at the equivalent of the finished probe diameter. Thus, after this operation, all of the mechanical machining on the probe tip was completed. Another method had been attempted early in the program which called for a second machining operation after copper plating to expose the ferrite at the pole face areas. However, it was difficult to avoid damage to the plated-copper shield during the second machining operation.

Considerable care and good techniques were required to carry out machining of the probe tip. The basic problem is to machine through both the ferrite and copper materials simultaneously. This machining was performed on a jewelers lathe under magnification. An abrasive cutting wheel was used for the entire operation.

## Assembly and Molding of Coils and Leads

The excitation and sensor circuit coils were wound on the appropriate ferrite shapes using a miniature coil-winding lathe under magnification. One-hundred turns of insulated magnet wire was wound on each coil. The ferrite pieces carrying the coils were then mounted on the ferrite pieces which extend to the probe body from the pole faces at the tip. The mating ferrite surfaces were always placed in intimate and direct contact to minimize the size of these air gaps in the magnetic circuits. The coil pieces were held in place by a bead of filled-epoxy adhesive (Bacon LCA-4) placed around, not between, the interfaces. Above the coil areas, two copper terminal strips were cemented on (and insulated from) each side of the central copper spacer structure. The fine magnet wires from the coils were soldered to the near ends of these terminal strips. Then, the large externally-shielded leads were soldered to the other ends of each terminal strip. The use of terminal strips avoids any stresses from the attachment or subsequent movement of the large external leads being applied to the delicate coil winding wires. Separate external leads were also soldered to each side of the central copper spacer for grounding purposes. With the coils mounted and all leads attached, the probe was then placed in a special fixture and the entire body above the tip was molded or potted in the LCA-4 epoxy material. The molding fixture was designed to engage the edges of the central copper spacer so as to center and align the probe and also to leave these surfaces uncoated for connection with the plated external copper shields.

## Masking and Plating the Probe

The final phase of the probe fabrication involved special masking and then copper plating of the external probe surfaces for shielding purposes. The first step was to apply a permanent insulative coating over the ribs of the internal copper spacer which extended between the two ferrite legs of each magnetic circuit for the length of the probe tip. This was accomplished by painting over these copper ribs with several coatings of a polyurethane resin (Conat 1155). Then it was necessary to apply a temporary plating maskant over both the precise pole face areas and the edge of the insulation line between the two halves of the central copper spacer. This latter maskant line had to follow the exposed edge of the central spacer completely around both sides of the probe body and tip. It had to cover the edge of the epoxy-glass laminate insulation layer, but left exposed most of the width of the edges of each of the adjacent copper layers of the central spacer. To provide this precision masking, a blue vinyl screening resist (Warnow 145-15-A) was painted on with an ultra-fine brush using magnification. The upper end of the probe body, where the external leads egress, was protected with plater's masking tape. The properly masked probe was processed through an electroless copper deposition sequence (McDermid 9073) to metallize the nonmetallic surfaces, i.e., the ferrite, epoxy, and polyurethane. (The blue vinyl resist was not cured by baking to minimize electroless copper deposition on the masked areas.) A thin layer (strike) of electrolytic copper was then deposited on the probe from a copper sulfate plating solution. Next, the probe was carefully inspected under magnification and additional blue vinyl resist was applied over any masked area which had accepted copper plating. The probe was then returned to the copper sulfate solution with a special "robber" attached to prevent excessive current density concentrations, and then electroplated with copper for about 15 minutes. The probe was then removed from the solution, measured, inspected, and remasked where necessary. Electroplating of copper was then resumed for another 15 min. This procedure was repeated until the necessary thickness of copper, about 0.002 in./in./surface for the 0.060 in. diameter probes, had been plated onto the probe tip. The entire tip was then masked with a heavy wax, after which plating was continued, to build up a copper thickness of about 0.005 in. on the probe body for additional shielding power. Finally, all of the wax and blue vinyl masking materials were stripped off in heated trichloroethylene. Isolated areas, where the initial copper plating had deposited over the maskant, were removed by etching away the excess copper in a solution of nitric and acetic acids. With all the maskants and any extraneous copper removed, fabrication of the probe was completed and each magnetic circuit was completely sheathed in a separate copper shield except at the pole face areas at the probe tip. Figures 17 and 18 show the complete 0.060 and 0.030 in. diameter double probes, respectively. The two pole-face areas and the longitudinal insulation line separating the two magnetic circuits in each probe can be clearly seen. Figures 19 and 20 show two views of the 0.060 in. diameter double probe. One pair of excitation and sensor pole face areas can be seen in Figure 19 as well as the insulation line separating the excitation and sensor sides of the probe. Figure 20 shows the double probe rotated about 90 deg to show the two (or double) set of pole faces on one circuitry side (either excitation or sensor).

Figure 17. Completed 0.060 in. Tip Diameter Single Probe
(20 Times Size)

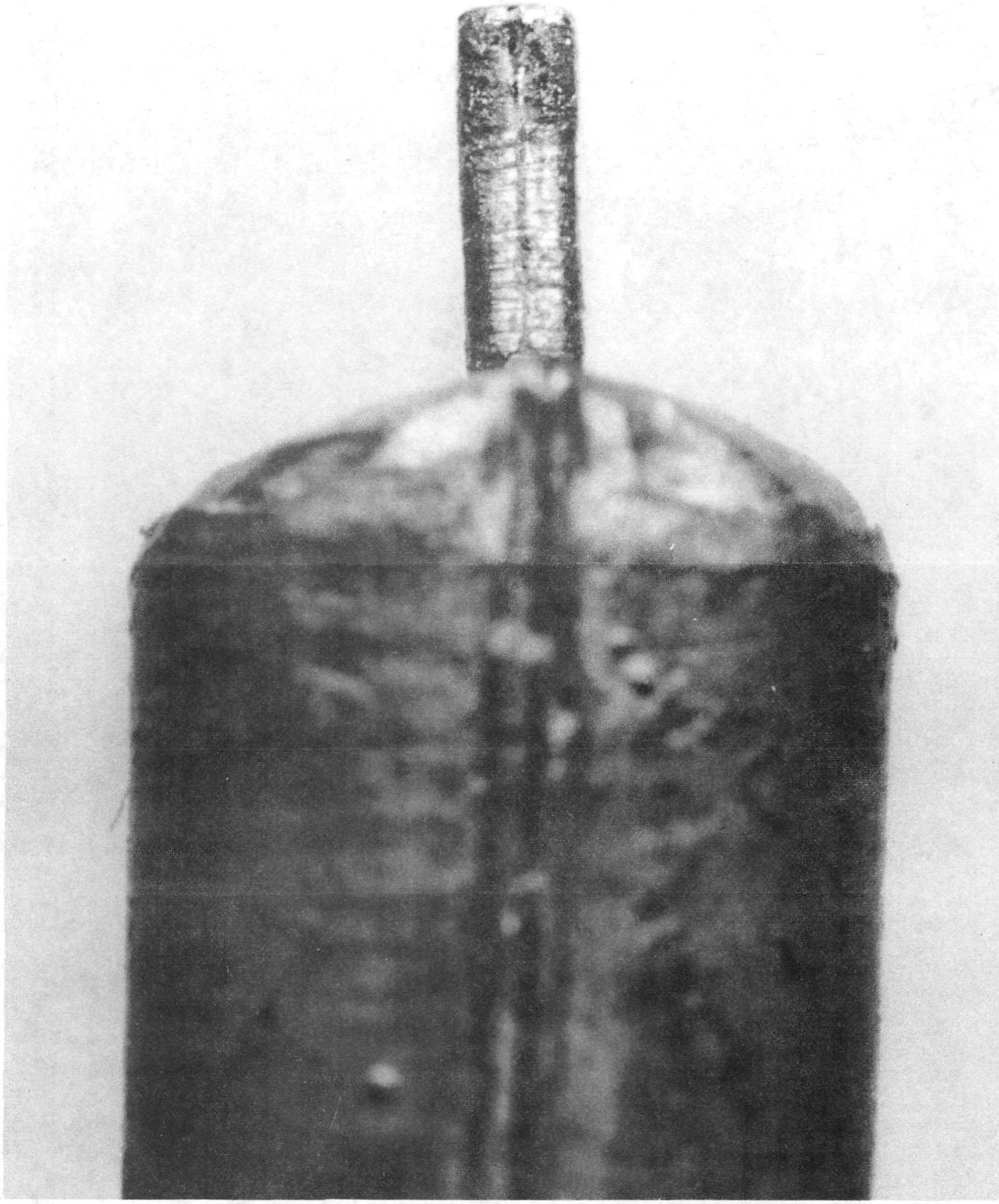

Figure 18. Completed 0.030 in. Diameter Tip Single Probe
(25 Times Size)

Figure 19. Completed 0.060 in. Tip Diameter Double Probe Showing One Set of Excitation and Sensor Pole Faces (22 Times Size)

Figure 20. Completed 0.060 in. Tip Diameter Double Probe Showing Double Pole Face Pairs of One Magnetic Circuit Side (22 Times Size)

## DESIGN AND FABRICATION OF TEST MULTILAYER BOARDS

To provide an appropriate vehicle for evaluation of the efficacy of the magnetic circuitry mutual coupling probes, a number of test multilayer boards were designed and fabricated. The purpose was to prepare multilayer boards with intentionally built-in plated-through-hole defects of the various types in question. Readings with the magnetic probes would then be taken in a sampling of the holes from each of the several boards. Afterwards, these same holes would be analyzed destructively to determine the actual structural condition of the plating and internal interconnections for correlation with the probe readings.

### Basic Test Board Design

A basic design for the test boards was established to represent a multilayer printed circuit board of realistic configuration and moderate complexity. Five printed circuitry layers were employed; three internal layers plus the two on the external surfaces. The first internal circuitry layer in from one side was left solid copper, except for a cross hatch of isolation spaces etched between the plated-through hole locations, so as to represent the ground or voltage plane frequently used in actual multilayer board designs. The isolation spaces were 0.020 in. wide on the master pattern for this layer. The other two internal layers, as well as the two surface layers, contained copper pads at each plated-through hole site which were connected in parallel rows by copper lines. All of the pads were 0.100 in. in diameter on the master patterns and the connecting lines were 0.025 in. wide. These layers were representative of the essential features of typical conductor patterns in actual multilayer boards.

Each test board contained an 8 × 8 square array of 64 plated-through holes. The hole sites were spaced 0.300 in. on centers in both directions. Two essentially duplicate sets of test boards were prepared. One set was fabricated with holes drilled to a diameter of 0.070 in. to be used with the 0.060 in. magnetic probes, and another set with holes drilled to a diameter of 0.040 in. for the 0.030 in. probe. The finished diameter of the holes was, of course, reduced by two to four thousandths of an inch by the addition of the through-hole plating. All of the test boards were designed so that the final laminated thickness was approximately 0.095 in. This dimension was chosen so as to be within the typical thickness range for actual multilayer boards and to be compatible with the 0.100 in. tip length of the magnetic mutual coupling probes.

Except for the special techniques described below to create selected defects, all of the test boards were made of G-10 epoxy-glass laminate materials and fabricated by conventional plated-through hole circuit board processes. The copper plating was electrodeposited from a standard pyrophosphate solution. Typical examples of the finished test boards are shown in Figures 21 and 22. All boards were fabricated by pattern solder plating the through holes and the

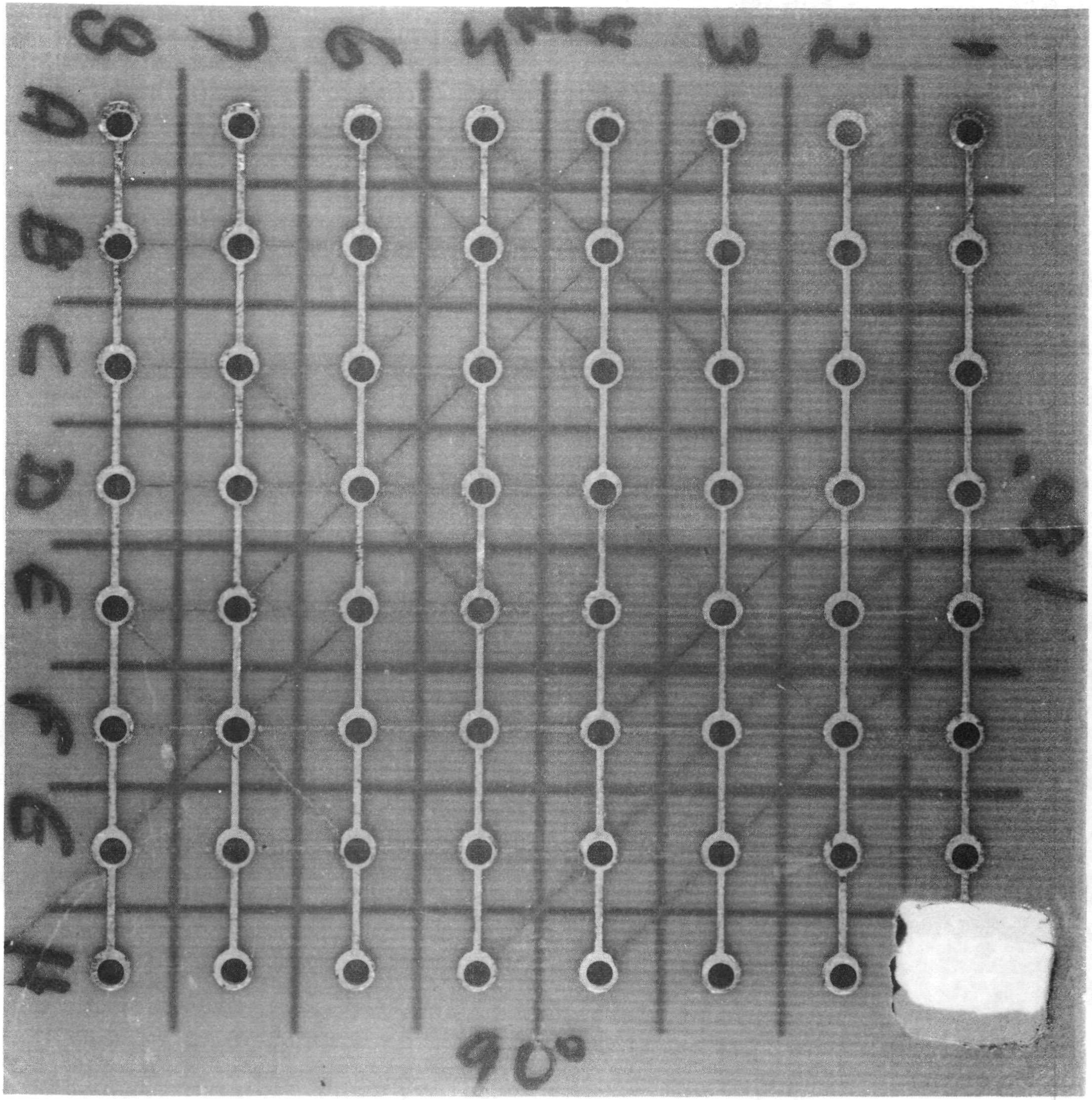


Figure 21. Typical Multilayer Test Board with Hole Size for Evaluation of 0.060 in. Probes

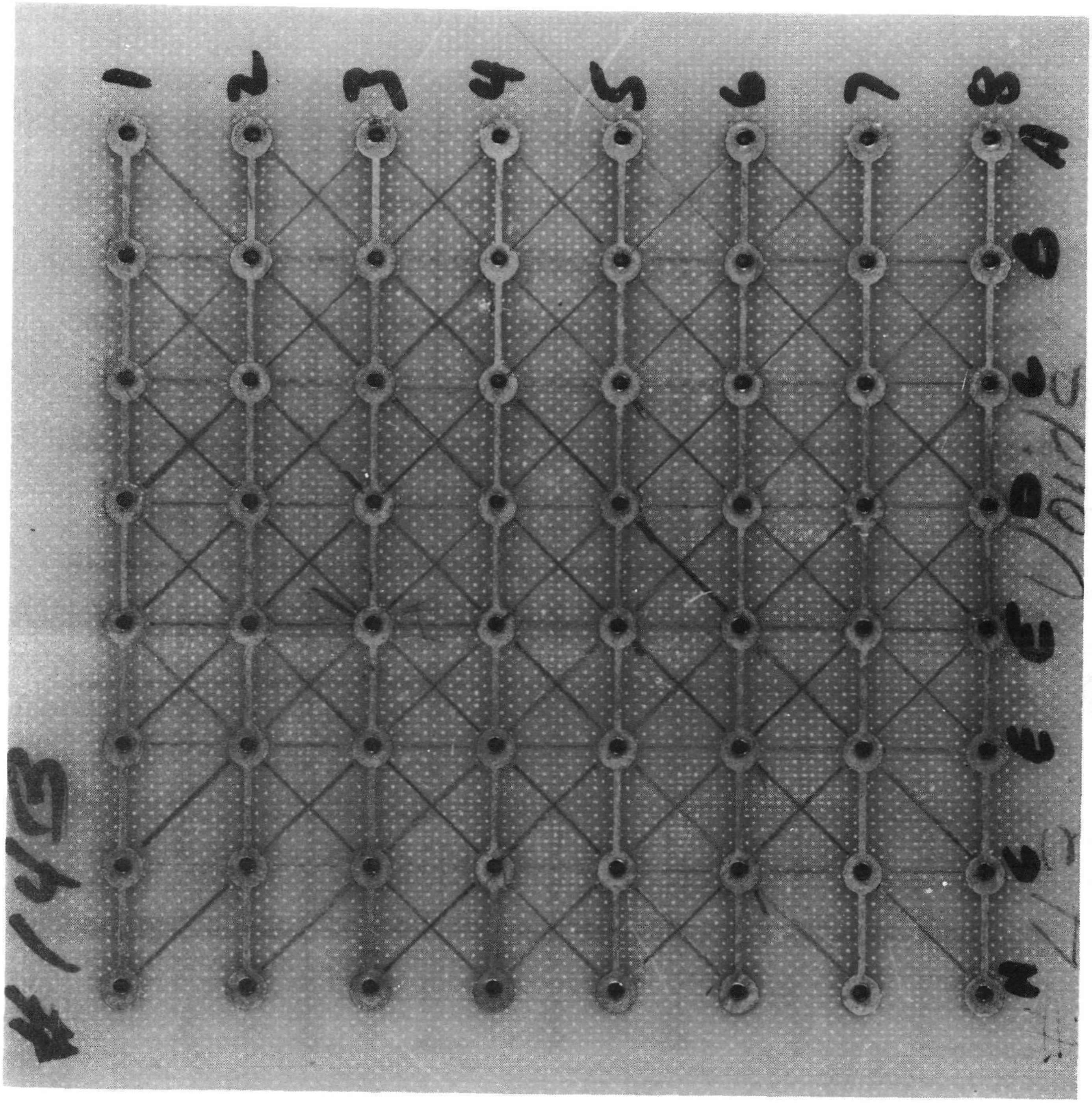

Figure 22. Typical Multilayer Test Board with Hole Size for Evaluation of 0.030 in. Probe

surface conductor patterns. The solder plating served as the resist for etching away the extraneous surface copper. In some cases, the solder was subsequently stripped off to leave the bare copper on the finished board.

In addition to the intentionally-defective boards, several test boards of each plated-through-hole size were fabricated entirely using the best production practices so as to be essentially defect free. These boards did in fact have good, structurally-sound plated-through holes and were used as testing standards against which probe readings from the boards with defective holes could be compared. Figure 23 is a photomicrograph of a metallographic cross section through a good plated-through hole from one of the standard boards. This figure serves to illustrate the internal configuration and typical layer-to-layer spacing of the basic test board design.

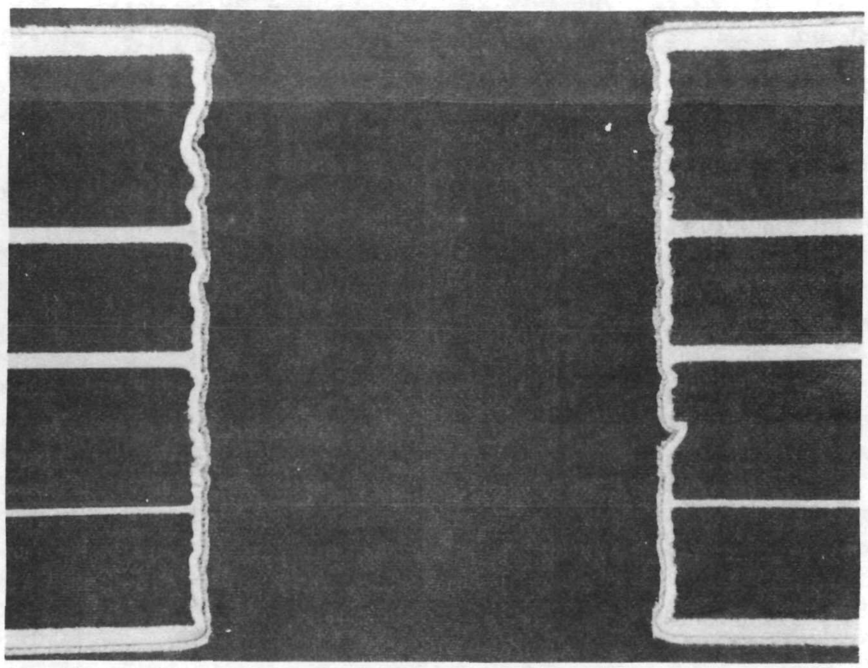

Figure 23. Photomicrograph (36X) of a Cross Section of a Typical Defect-Free Plated-Through Hole in a Standard Multilayer Test Board.

The lay-up and construction of the test boards were all such that one outer surface conductor layer and the internal ground plane were on the opposite sides of one double-copper foil-clad thin epoxy-glass laminate, the two internal conductor layers were on the opposite sides of another thin double-clad laminate, and the other surface conductor layer was on a single-clad thin laminate. The inner layer patterns were etched before lamination, while the outer layers were plated and etched after lamination.

## Separation or Gap Defects

The so called separation or gap defect occurs not in the plated-through hole proper, but between the hole wall and an internal layer conductor pad through which the hole passes and is intended to connect. The defect is simply a lack of metal-to-metal contact and metallurgical bonding between the hole-wall plated copper and the surronding copper pad for part or all of the hole circumference. This condition is usually caused in production multilayer boards by a barrier of epoxy resin from the epoxy-glass laminate material which is smeared over the copper pad surface during drilling and is not removed before through-hole plating. One way to fabricate a multilayer test board with built-in separation defects would be to intentionally cause the foregoing sequence of events to occur. This was one of the approaches used to produce separation defects in some test boards for this study. However, by this method the separations tend to be thin and of erratic occurrence. Also, it is not really possible to control the circumferential length of the separation. Thus, another method was used to build in separation defects of a more predetermined size. This method involved removing a prescribed area of copper from within each internal pad before lamination and drilling. It was felt that the more pronounced separation defect would be particularly useful in the initial evaluation of the sensitivity of the probe.

The test multilayer boards with the larger type separation defects were fabricated as follows. First the master pattern negative photo transparencies for the internal conductor pattern layers were modified by taping on to each clear pad area an opaque circle with a diameter of 0.060 in. The opaque circle was offset to within 0.010 to 0.015 in. of one edge of the 0.100 in. diameter pad area. The offset of the opaque circles was in the same direction for all pads in a row, but for each succeeding row, the direction of offset was rotated approximately 90 deg. Then the thin, double copper-foil clad epoxy-glass laminate for the two internal conductor pattern layers was coated on both sides with a dry-film photoresist. The photoresist was then exposed through the modified master pattern and developed to obtain the positive resist image on both copper surfaces. Because of the opaque circles on the modified master patterns, a circular area within each pad area was not covered with resist. Thus, when the extraneous copper was etched away by conventional means to leave the conductor pattern, a circular area of copper was also etched out of each pad area. The thin laminate with these specially created conductor and pad patterns on each side was then laminated together with the other appropriate pieces to form the multilayer board structure. The etched-out areas in the internal copper pads were filled with epoxy from the preimpregnated epoxy-glass lamination adhesive material (prepreg) during the lamination process. Next the test board was drilled. However, when the drill passed through the internal pads, the copper was exposed only part of the way around the hole. The rest of the hole exposed only the epoxy that had filled in the etched out area. Finally, when the holes were plated, the separation defect was created between the hole-wall plating and the remaining copper pad beyond that area which had been originally etched away. Ideally, if the etched-out area in the external pad was accurately positioned, and if the drill passed through the exact center of the pad, the separation defect would extend along about 100 deg around the plated wall of the 0.070 in. diameter drilled holes. In the actual test multilayer boards, a range of gap sizes was produced because of the interaction of the normal dimensional alignment tolerances from the various fabrication process steps. Six test multilayer boards with this type of built-in separation defect were fabricated with 0.070 in. drilled holes and two with 0.040 in. holes. Figure 24 shows a typical separation defect in one of the test boards fabricated by this method.

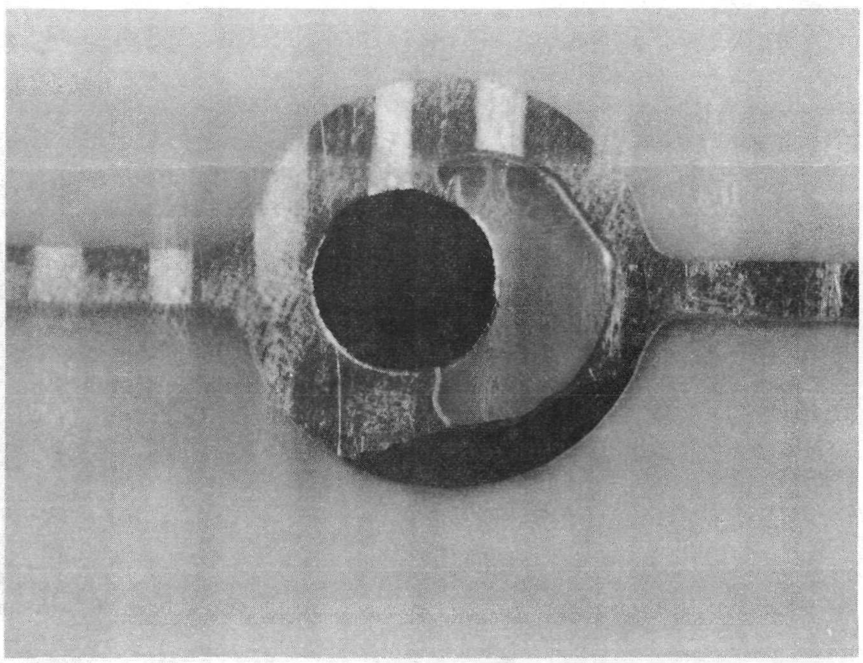

Figure 24. Photomacrograph (25X) of a Section Through an Internal Pad Showing Typical Separation from the Plated-Through Hole Produced by Special Etching.

Test boards with gap or separation defects were also fabricated by intentionally building in a resin smear over the internal through-hole pad connecting surfaces. The first step here was to cause a significant amount of resin smear to be formed during the hole drilling operation. Such a condition was obtained very readily with a dull drill bit operated at slower than normal speed and feed rate. With these parameters, there was considerable heat buildup as each hole was drilled, which melted the epoxy resin along the hole wall. The movement of the drill then spread the melted epoxy in various degrees over the internal copper layers penetrated by the hole. The subsequent hole wall etch-back process was omitted so as not to remove the smeared epoxy. Otherwise, the boards were taken through the standard production fabrication sequence. Figure 25 shows a typical separation defect produced by the smeared epoxy method. Two test multilayer boards of this type were fabricated with 0.070 in. drilled holes and two with 0.040 in. holes.

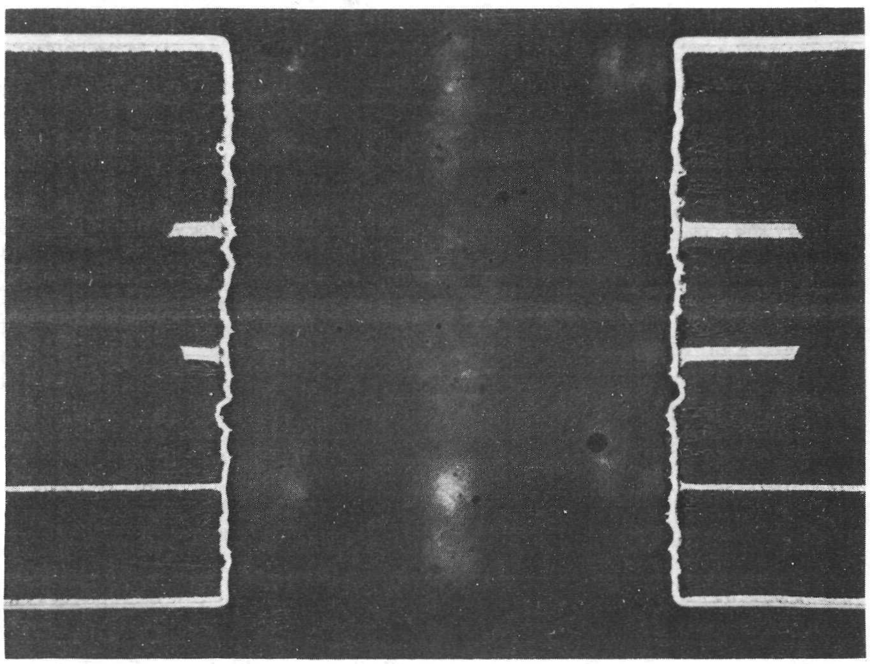

Figure 25. Photomicrograph (35X) of a Cross Section of a Typical Plated-Through Hole with Separation Defect Produced by Smeared Epoxy Resin

## Hole Wall Void Defects

Voids in the hole-wall plating are the second type of critical defect to be built in to test multilayer boards for mutual coupling probe evaluation. The term voids describes any condition where a given area, large or small, of the through-hole wall is not covered with plated metal. The plated metal is normally copper, with or without an overplate of solder or gold. Voids as such, can arise by either of two basic mechanisms during multilayer fabrication. First, the void area may not have been metallized or plated with copper at all. This is usually caused by failure of the electroless copper deposition process to coat the particular area. Second, the void area may have been properly plated with copper which was then removed during the conductor pattern etching process. This can be caused by a break in the gold or solder overplate, or an organic resist material which allows the etchant access to the underlying copper.

Both of the foregoing mechanisms can and do occur in multilayer board production and both result in essentially the same type of structural void defects. For this study, test boards with void defects were fabricated by artificially creating the conditions for the etching away mechanism since it is much more suitable for control of the number and location of the defects. Since the basic test board fabrication method involved solder plating the outer layer conductor patterns and the through holes, a straightforward means to create voids was to make small breaks or pinholes in the solder prior to etching. This was accomplished with a needle point probe under a microscope. Various sizes and shapes of breaks in the coating of solder on the hole walls were made from single pinholes, to line scratches, to larger holes and strings of pinholes. When the boards were etched, the etchant attacked and dissolved the copper where the solder had been broken to create the void defects. The solder was then either stripped off or flowed by immersing the board in hot oil. The resulting voids were always somewhat larger than the original openings in the solder because of the undercut effect during etching. Overall, a range of void defect types were successfully produced in test multilayer boards which are very representative of those encountered in actual production. Characteristic void defects in holes from the test boards are shown in Figure 26. Two test boards with void defects were fabricated for each plated-through hole size.

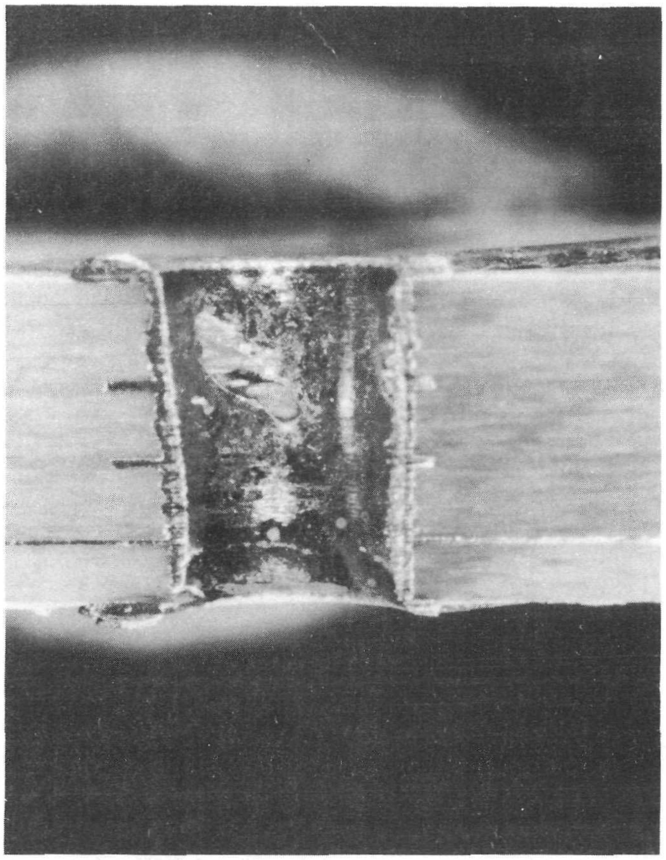

Figure 26. Photomacrograph of a Section Through a Typical Plated-Through Hole with an Etched-In Void Defect.

## Cracked Hole Plating Defects

Cracks in the through-hole plating are another critical defect, particularly because cracks can propagate and enlarge over a period of time and are aggravated by the repeated temperature changes often encountered in field service. Cracked plating in multilayer board holes arises from the stresses caused by the considerable difference in thermal expansion of the copper and the epoxy-glass laminate. Whether or not cracking will occur in the plated-through-holes of a particular multilayer board depends both on the properties of the plated copper and on the thermal stresses to which the board is subjected. Generally, a brittle copper electrodeposit, with relatively low elongation and tensile strength is very prone to cracking. A single exposure to sufficiently high-temperature conditions tends to cause cracks because the thermal expansion stress exceeds the elongation limits and tensile strength of the copper. These cracks often appear first at the shoulders of the holes, i.e., at the angle where the hole-wall plating bends into the surface plating. Repeated cyclic exposure to less extreme high temperatures tends to cause cracks due to work hardening and fatigue of the hole wall copper plating. These cracks usually occur in the barrel of the hole, often first near the mid-plane of the board.

Test boards with built-in cracked hole plating defects were fabricated by taking advantage of all of the factors described above. First, the through-hole copper was electroplated from a solution especially prepared to yield a brittle, inelastic deposit of moderate tensile strength which was known to be very susceptible to cracks. In essence, the special solution was a conventional copper pyrophosphate plating bath which contained an excess of organic material from an additive agent and its breakdown products. The completed boards were then subjected to either two or three immersions in the hot solder flowing oil at 400 F or up to 20 cycles in air from -65 to +300 F. These procedures produced the various types of through-hole plating crack defects as illustrated in Figure 27. Two test multilayer boards of each size were fabricated with crack defects.

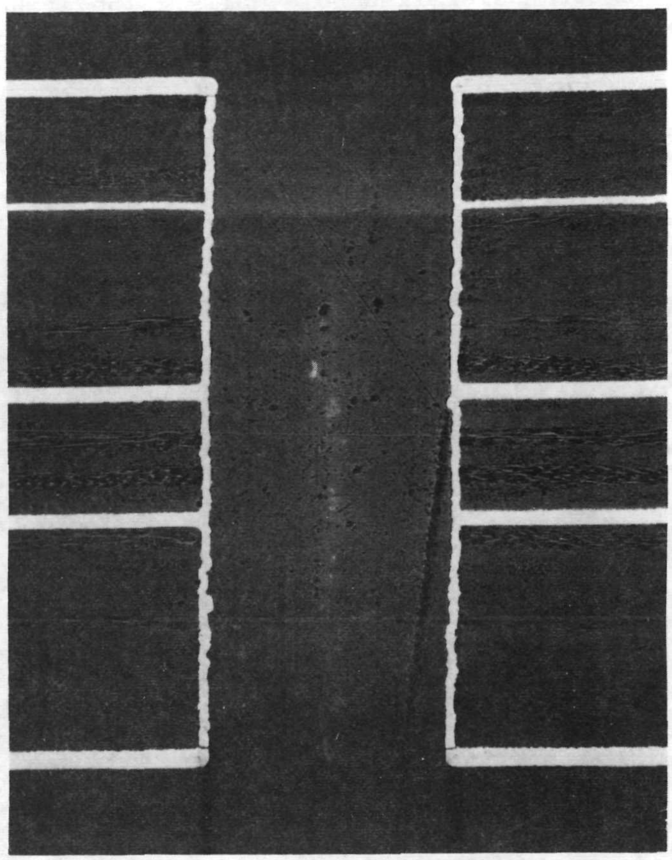

Figure 27. Photomicrograph (35X) of a Cross Section of a Typical Plated-Through Hole with Crack Defects.

## Rough, Thick-Thin Hole Plating Defects

The final type of critical plated-through-hole defect which was considered in this study is a rough hole wall combined with irregular plating thickness. This overall hole condition generally occurs in actual production multilayer boards because the rough hole wall typically causes or aggravates thick-thin or modular copper plating. The rough hole wall usually originates with the drilling operation but can be due to an uneven attack by the etch-back process. Also, certain parameters of the copper plating process can also be selected so as to tend toward a modulation or uneven thickness of the deposit in through holes.

The defect type in question was built into test multilayer boards primarily by modifying the drilling operation. A worn drill bit of nonoptimum tip geometry was used at a slower than normal feed rate. This produced very rough, irregular, and somewhat torn as-drilled hole walls. The etch-back process was then omitted so as not to have any chemical smoothing effect on the hole walls. Also, the copper plating process was carried out at a slightly higher than normal current density. The net result was to produce quite rough finished holes with distinctly thick-thin copper plating as illustrated in Figure 28. Two test multilayer boards of each hole size were fabricated with this type of defect.

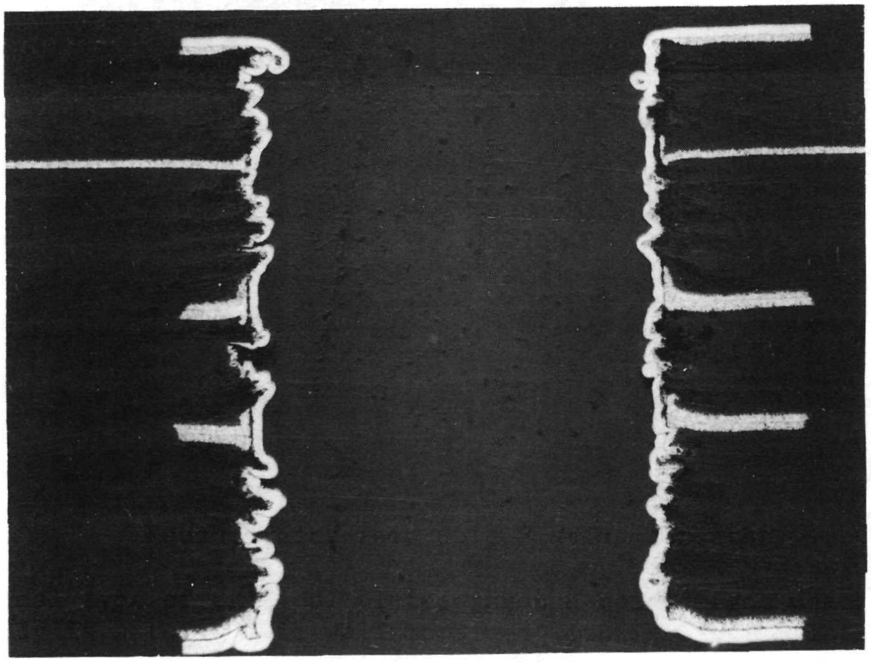

Figure 28. Photomicrograph (35X) of a Cross Section of a Typical Plated-Through Hole with Intentionally Rough Walls and Thick-Thin Plating.

Multilayer printed circuit boards fabricated with the various defects in the plated-through hole were used to obtain operational data on all three probe designs. A plated-through hole was thoroughly interrogated by recording the sensor output voltage for eight, equally spaced angular positions 45 deg apart as the probe was inserted into the hole in 0.005 in. increments. All interrogation procedures were the same for each hole. The starting orientation was as shown in Figure 29 with the sensitive area of the probe held firmly in contact with the hole wall. The initial starting depth was to have the midpoint of the excitation pole face gap even with the top of the board surface circuitry. Table IV shows the number of holes and types of defects for which data were obtained with each probe.

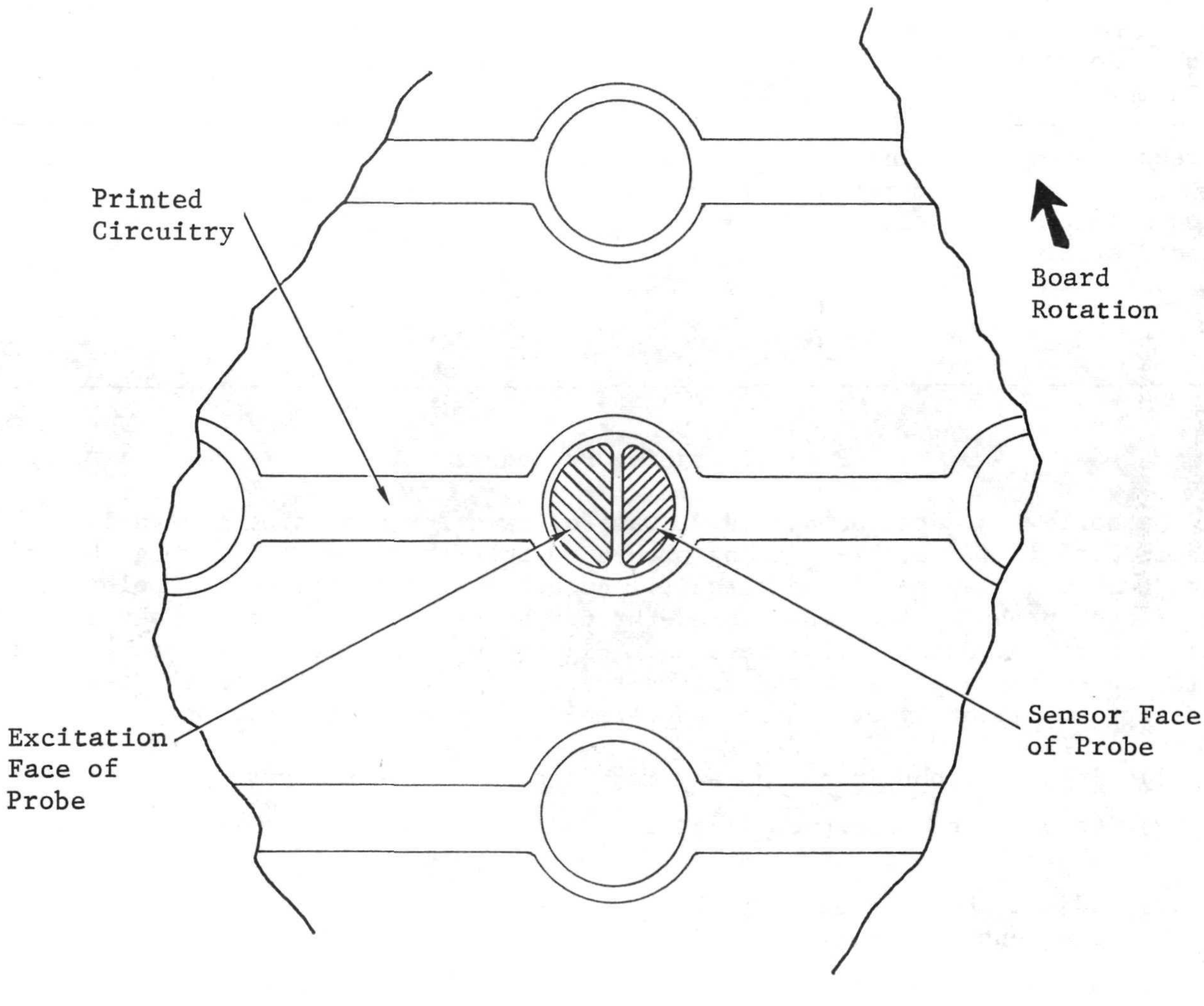


Figure 29. Probe Orientation for Testing

TABLE IV
SUMMARY OF DEFECTIVE PLATED-THROUGH HOLES INTERROGATED WITH
EACH MAGNETIC CIRCUITRY MUTUAL COUPLING PROBE

| | Number of Holes Interrogated with Each Probe | | |
|---|---|---|---|
| Test Board Defect Type | Double Probe 0.060 in. | Single Probe 0.060 in. | Single Probe 0.030 in. |
| Standard-No Defects | 13 | 3 | 3 |
| Separation Between Hole Wall and Pad | 8 | 8 | 3 |
| Voids in Hole Wall Plating | 5 | 3 | 3 |
| Cracks in Hole Plating | 7 | - | 5 |
| Rough-Thick-Thin Walls and Plating | 6 | 6 | - |
| | 39 | 20 | 14 |

## Probe Operating Procedure

The following detailed procedure was followed for operating the various magnetic-circuitry, mutual-coupling probes to interrogate plated-through holes in the test multilayer printed circuit. Accurate positioning at the pole face area of each probe against the plated-through-hole wall under test was very critical for reproducible measurements. Figure 30 shows one of the probes with its tip inserted in a test board plated-through hole. Markings on the test board serve to identify each hole and establish the angular positions.

(1) Install probe in holder and mount holder on height gage.

(2) Connect the probe, oscillator, amplifier, and voltmeters as shown in Figure 31.

(3) Adjust the frequency of the test oscillator to the desired frequency (approximately 500 kHz)

(4) Adjust the output level of the oscillator to obtain an excitation current of 20 ma. Measure the current by measuring the voltage across the 1-ohm resistor.

(5) Position the probe in the circuit board hole so that the air gap is at the desired depth.

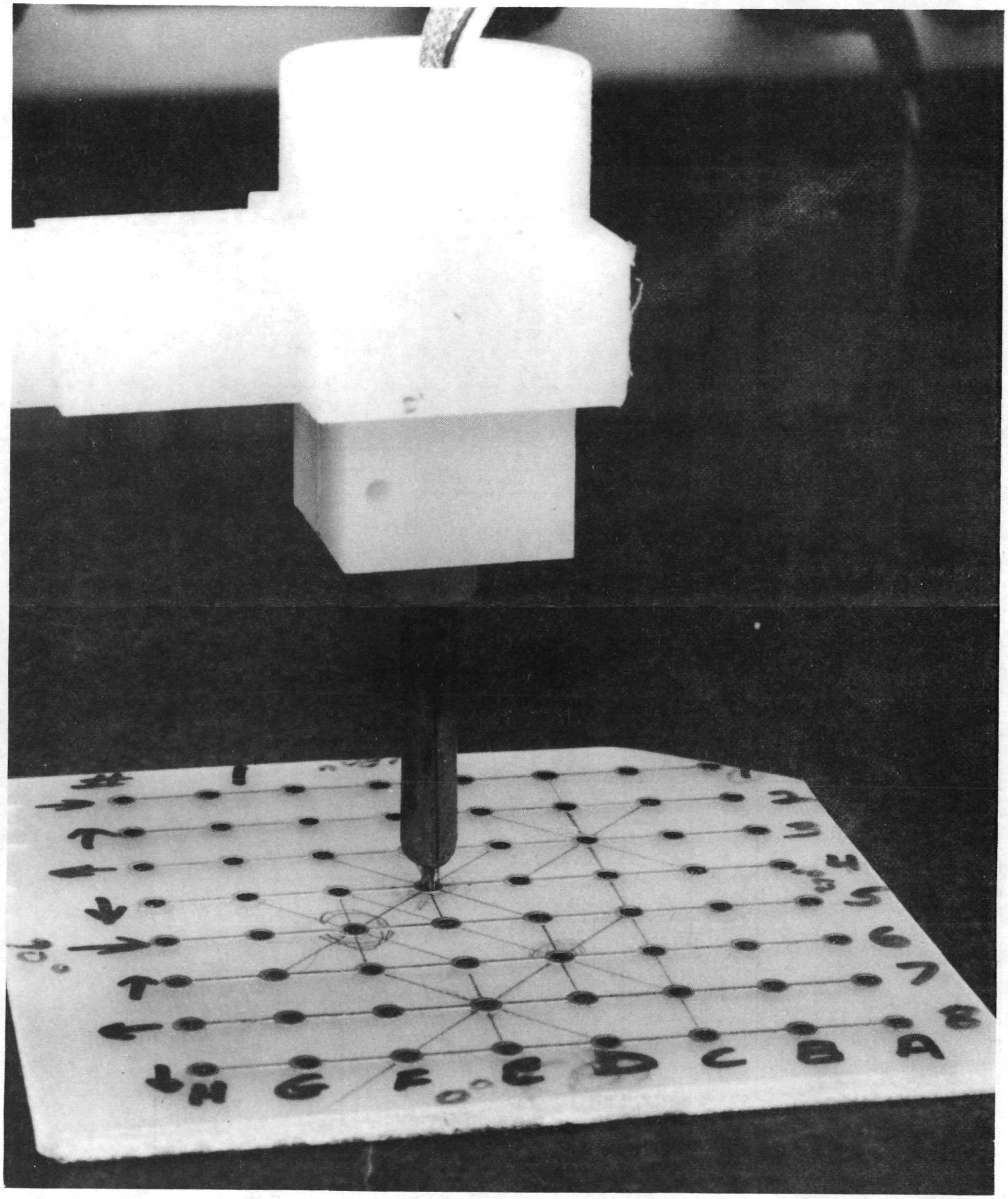

Figure 30. Mutual Coupling Probe with Tip Inserted in a Test Board Plated-Through Hole

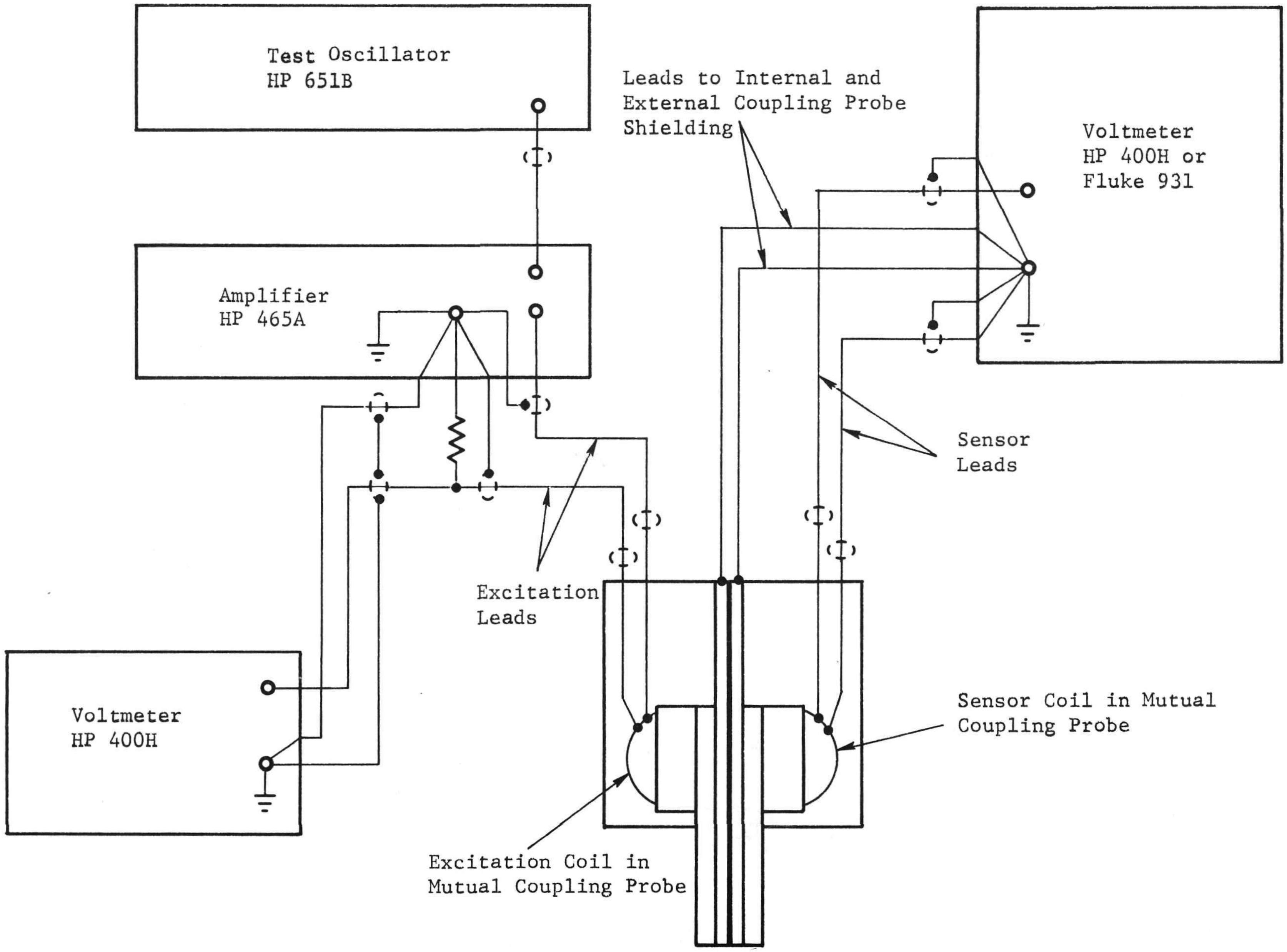


Figure 31. Probe Test Circuit

(6) Position the circuit board so that the sidewall of the hole is tight against the split between the excitation and sensor poles on the probe.

(7) Measure and record the sensor voltage. When measuring the output of a probe with high direct coupling, use the differential voltmeter to obtain the required sensitivity.

(8) Reposition the circuit board 45 deg to obtain another sensor output reading at the same depth.

(9) Repeat steps 7 and 8 to obtain a total of 8 readings.

(10) Lower the probe 0.005 in. and repeat steps 7, 8, and 9.

(11) Repeat step 10 to obtain the sensor output readings at all the desired depths.

## Accessory Probe Equipment

The following items of accessory equipment were employed for operating the magnetic-circuitry, mutual-coupling probes for interrogation of plated-through holes in the test multilayer boards. All of the items listed are commercially available, off-the-shelf equipment, except for the probe holder which was designed and fabricated specifically for this program. Figure 32 shows one of the probes in position to interrogate a plated-through hole in a test multilayer board, and all of the accessory equipment.

| Item No. | |
|---|---|
| 1 | Oscillator, Test, 100 kHz to 1 MHz, dial accuracy $\pm 3$ percent, output variable up to 3.16 v into 50-ohm load, Hewlett Packard Model 651A. |
| 2 | Amplifier, frequency range 100 kHz to 1 MHz, output voltage greater than 10 v rms, output impedance less than 50 ohms, Hewlett Packard Model 465A. |
| 3 | Voltmeter, $\pm 2$ percent full scale 100 kHz to 1 MHz, input impedance 10 Meg shunted by 35 pf, Hewlett Packard Model 400H. |
| 4 | Voltmeter, differential, $\pm 3$ percent, 500 kHz to 1 MHz, 5 μv resolution, 0 to 500 mv range, Fluke, Model 931. |
| 5 | Resistor, $1 \pm 0.1$ ohm, 1/2 w, noninductive |
| 6 | Gage, Height, Vernier, 18 in. graduations in thousandths of an inch, Starrett No. 454-18 |
| 7 | Plate, Surface, 18 × 12 × 4 in., Collins Micro Flat |
| 8 | Holder, Probe, NR Sketch No. SK 01335 |

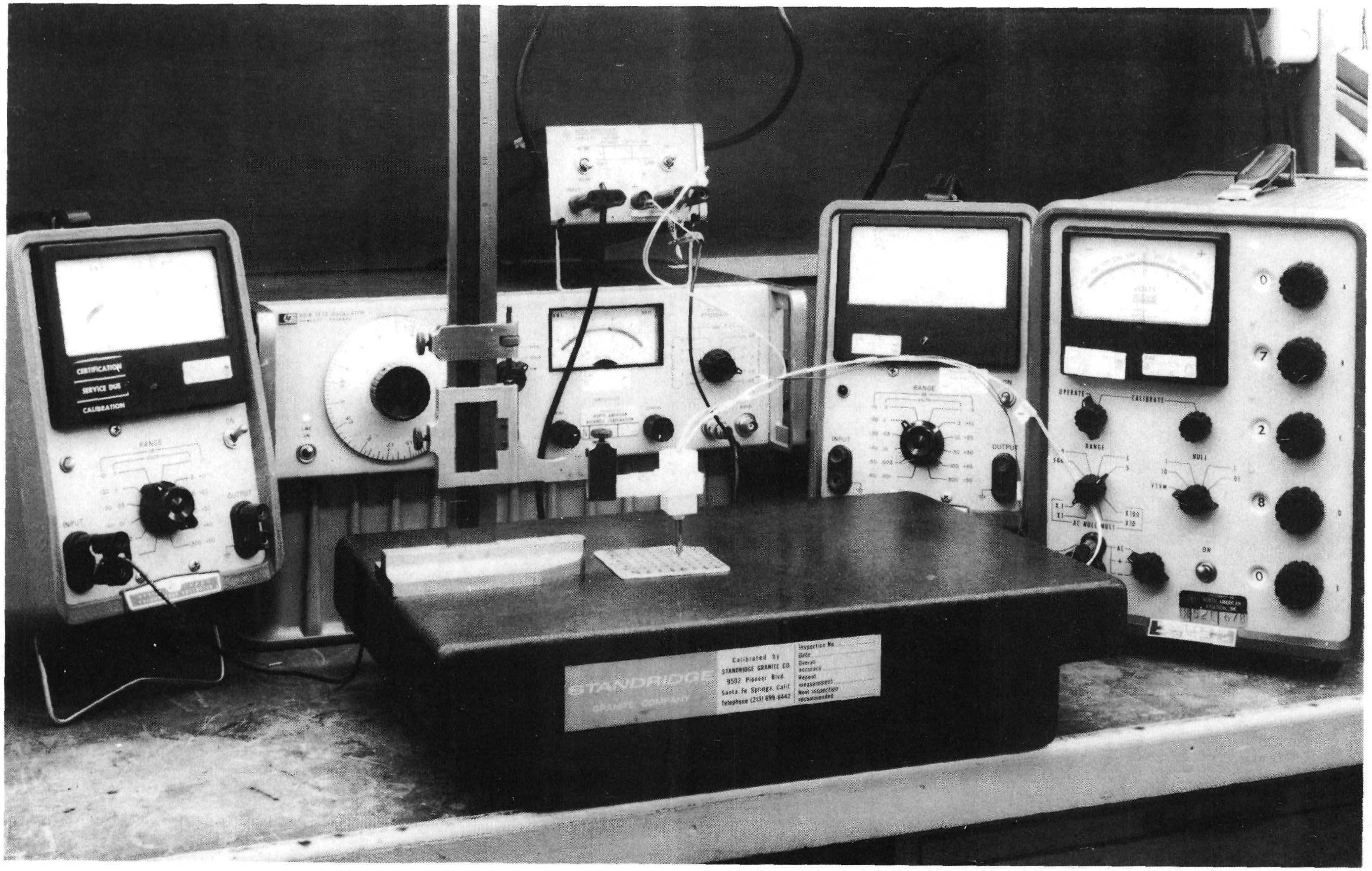


Figure 32. Mutual Coupling Probe in Position to Interrogate a Plate-Through Hole in a Test Multilayer Board with All Accessory Equipment

## Probe Testing Results

Graphic plots of interrogation data from each hole were made for comparison of the response of each probe to the various defects. These plots were simplified by showing sensor output voltage as a function of probe depth in a hole, with a bandwidth representing the extremes of the variations of the probe output signal for the eight angular positions at each depth. The plots of data obtained on holes with no defects were used as a standard in determining the probe response to holes with the various kind of defects. Each of the probe designs has its own characteristic changes of signal level as a function of probe depth in the hole. No explanation for this characteristic was determined.

### 0.060 in. Single Probe

The typical response of this probe to the various plated-through-hole defects was measured by the procedure described above. The characteristic curve shape and data bandwidth for a plated-through hole with no defects are shown in Figure 33 (Board 3B, Hole 3E). A section view of this hole is shown in Figure 34.

The detection of the presence of a void in a plated-through wall is shown by Figure 35 (Board 5, Hole 5E). The increased sensor output range indicates a defect near the top of the hole and is verified by the section view in Figure 36.

The probe data, Figure 37 (Board 1, Hole 6D), gives no indication of a separation gap defect. Figures 38 and 39 show pronounced gap defects between the hole wall and each of the internal conductor pads.

Figure 40 (Board 7, Hole 6B) shows essentially no probe response to rough wall defects. The presence and degree of roughness in this hole is shown in Figure 41. Some separation defects are also present.

Examination of Figure 42 (Board 6, Hole 5E) indicates no definite response to smear separation defects. Smeared resin that separates the pad and wall almost completely is shown at both pad levels in Figures 43 and 44. This probe shows response to voids in a plated-through-hole wall, but apparently no useful response to other defects.

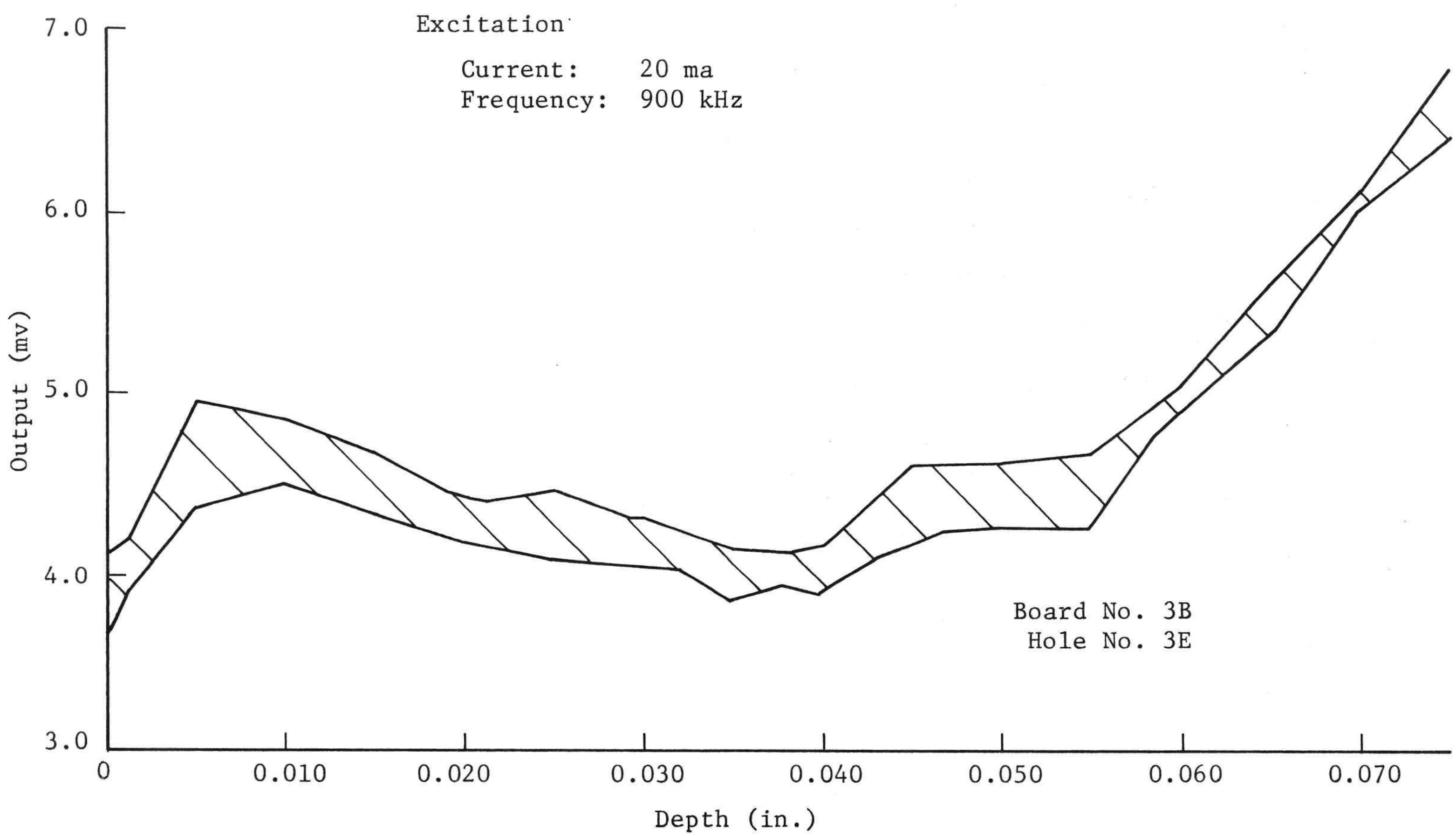


Figure 33. Sensor Output Range with Angular Rotation of 0.060 in. Single Probe in Plated-Through Hole with No Defects

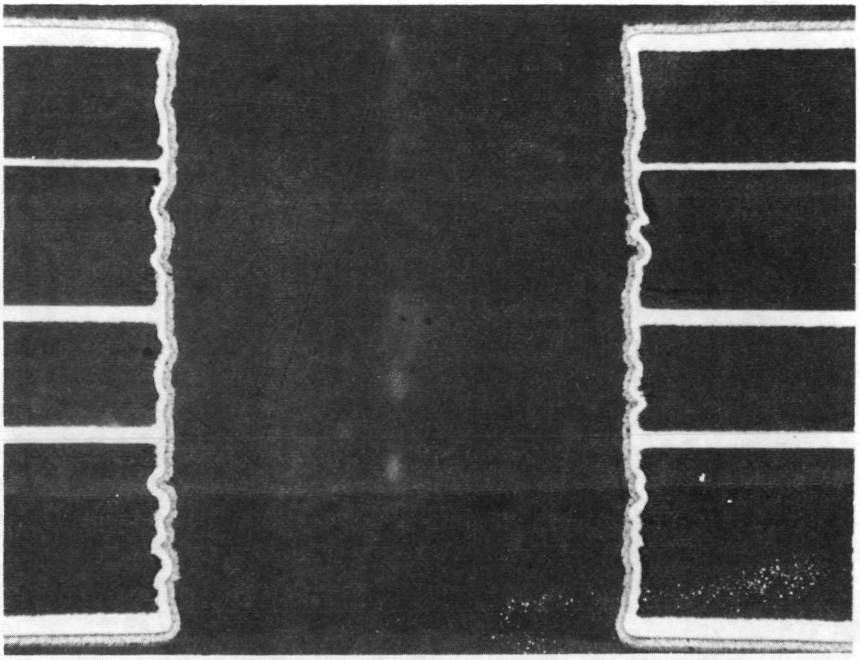

Figure 34. Photomicrograph (36X) of a Cross Section of a Plated-Through Hole from a Standard Test Board Used to Obtain the Data in Figure 33.

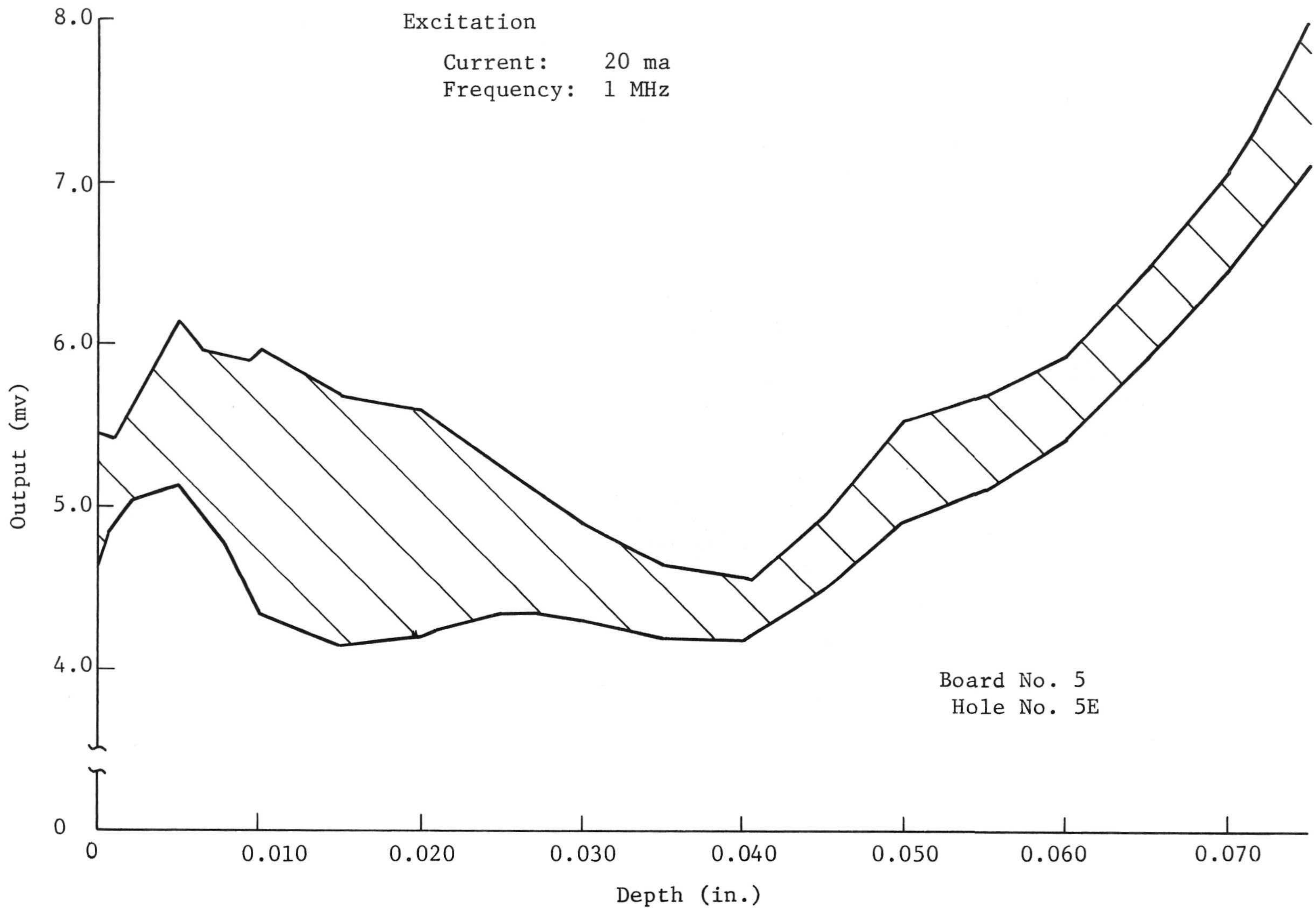


Figure 35. Sensor Output Range with Angular Rotation of 0.060 in. Single Probe in Plated-Through Hole with Void Defect

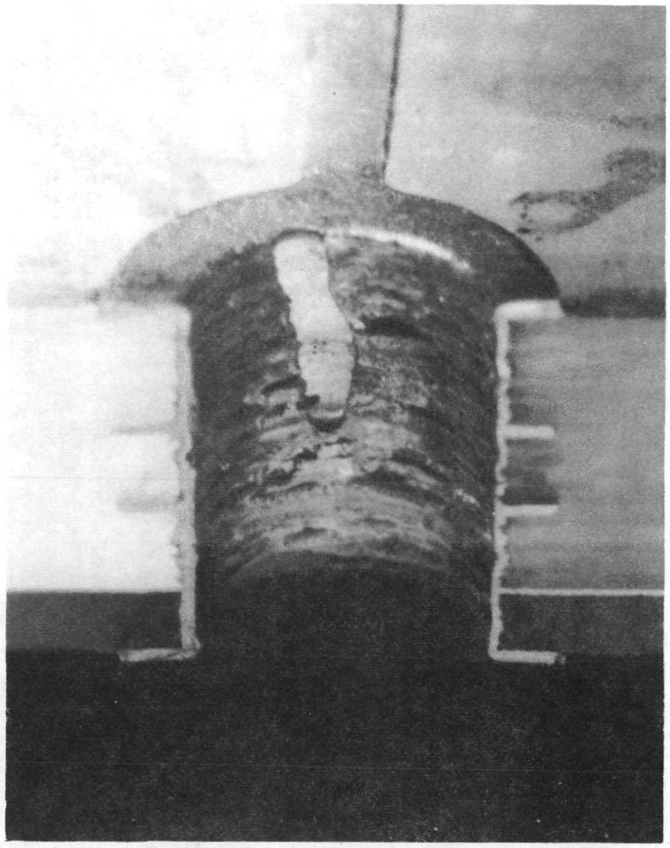

Figure 36. Photomacrograph (24X) of a Sectioned Plated-Through Hole with Void Defect Used to Obtain the Data in Figure 35.

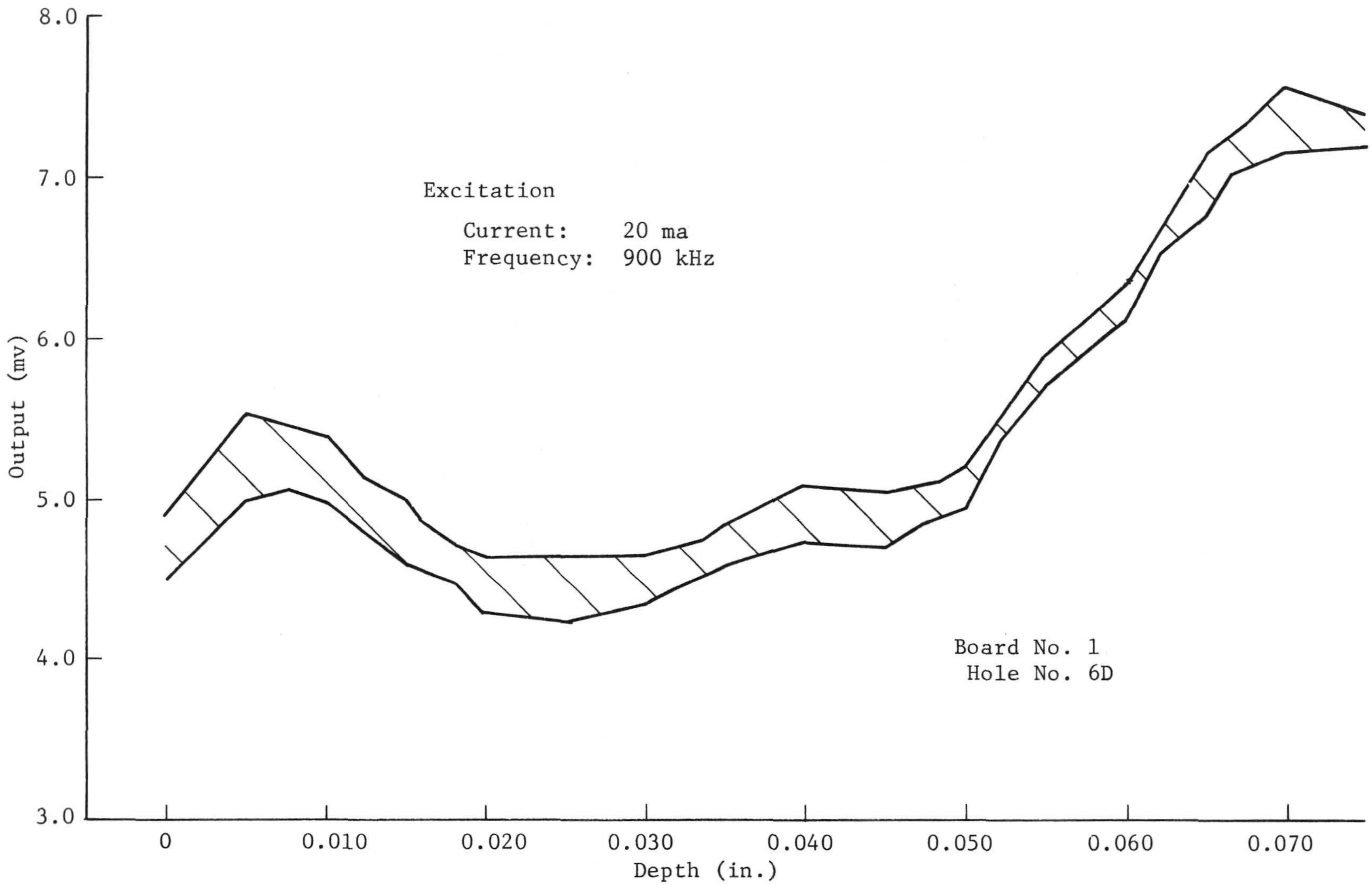


Figure 37. Sensor Output Range with Angular Rotation of 0.060 in. Single Probe in Plated-Through Hole with Gap Defect

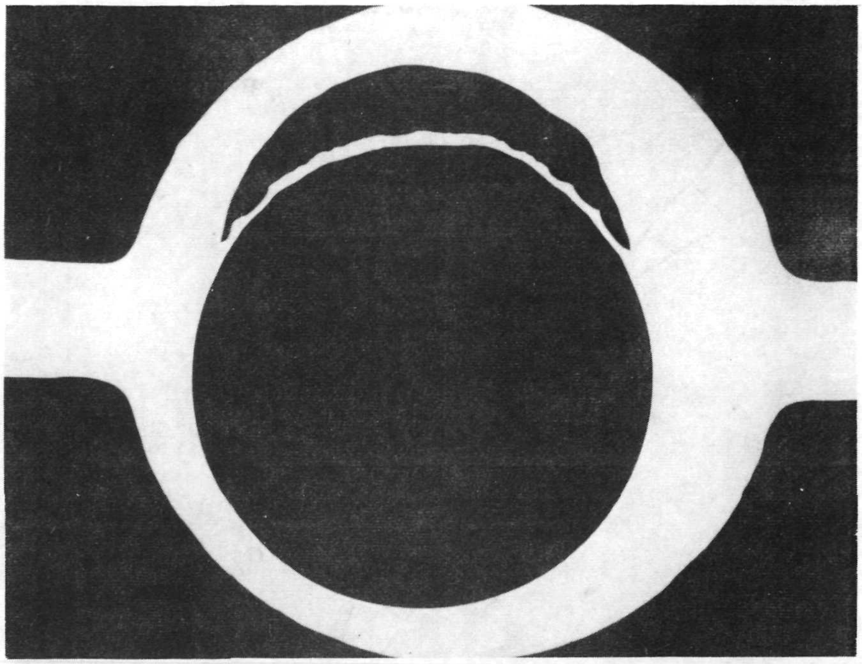

Figure 38. Photomicrograph (36X) of a Cross Section Through the First Internal Pad Showing Separation from the Plated-Through Hole Used to Obtain the Data in Figure 37.

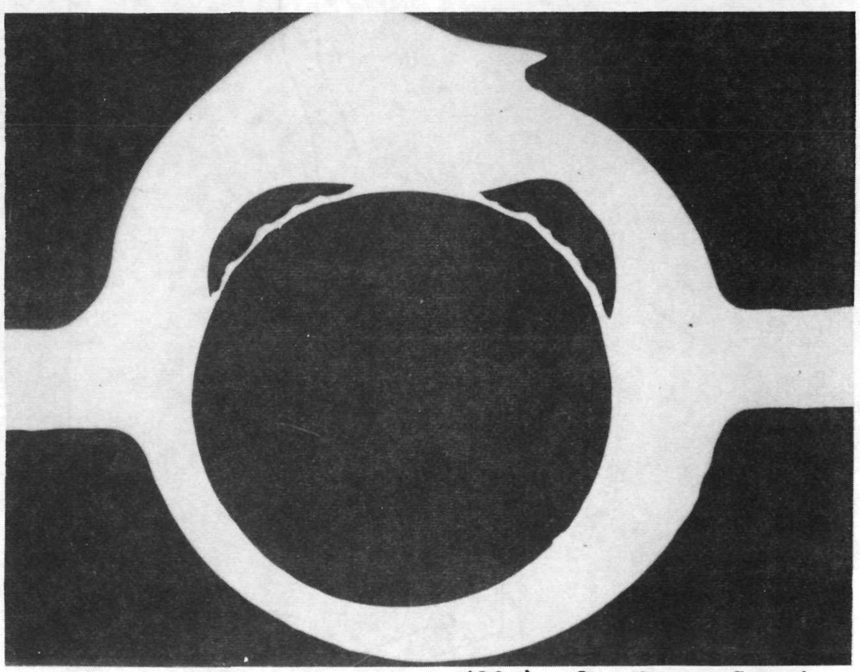

Figure 39. Photomicrograph (32X) of a Cross Section Through the Second Internal Pad Showing Separation from Plated-Through Hole Used to Obtain the Data in Figure 38.

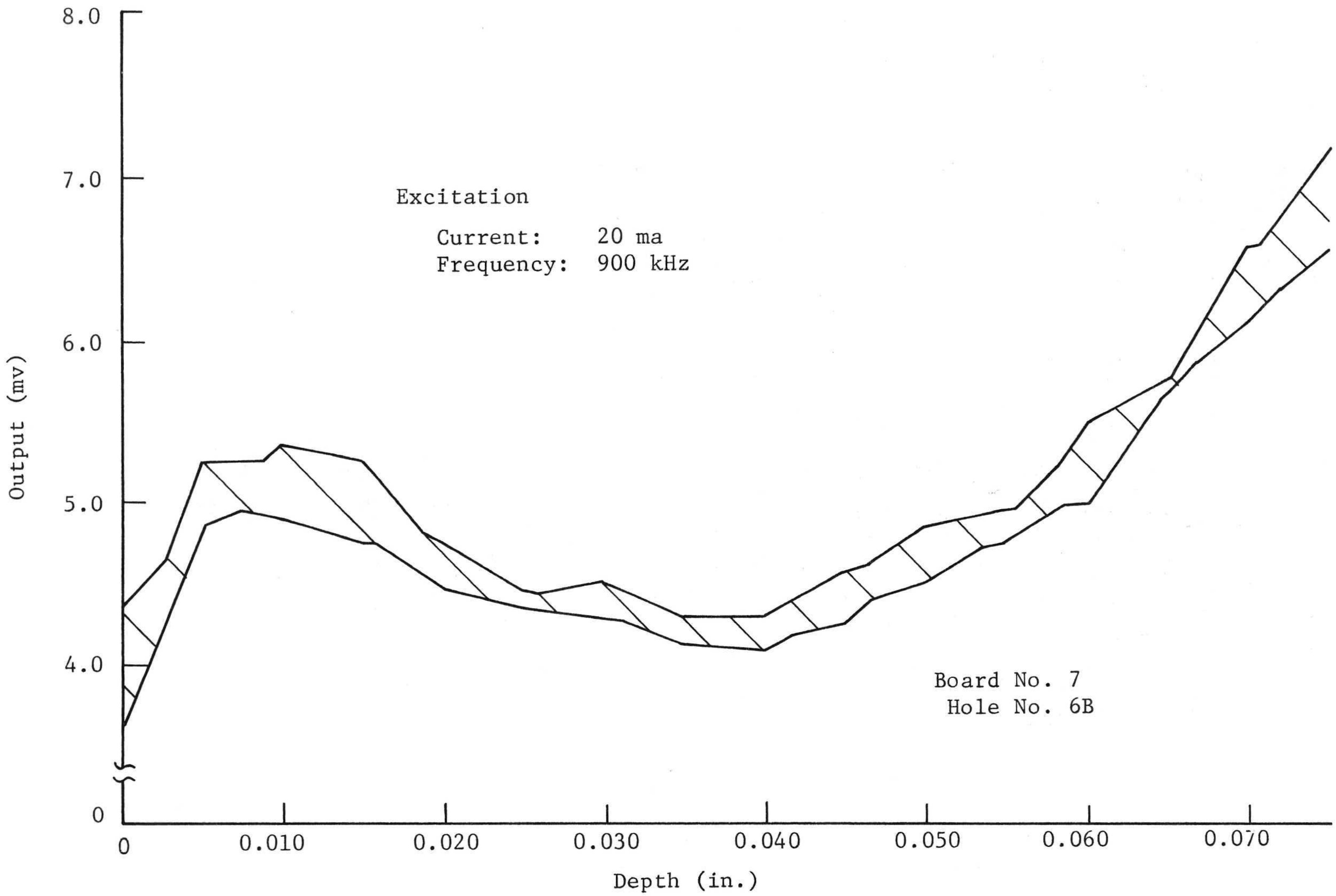


Figure 40. Sensor Output Range with Angular Rotation of 0.060 in. Single Probe in Plated-Through Hole with Rough Wall Defects

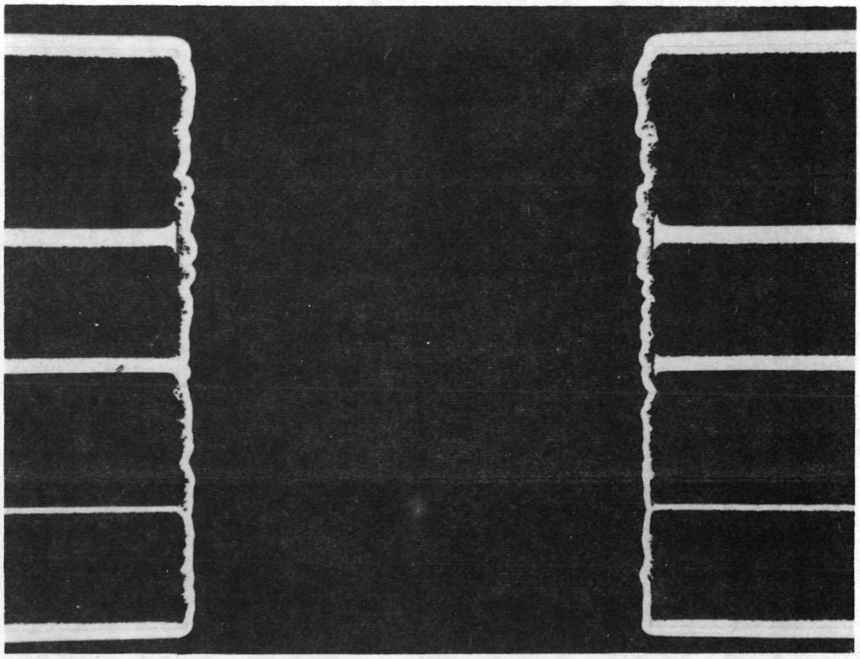

Figure 41. Photomicrograph (36X) of a Cross Section of Plated-Through Hole with Rough Walls and Some Separation Defects Used to Obtain the Data in Figure 40.

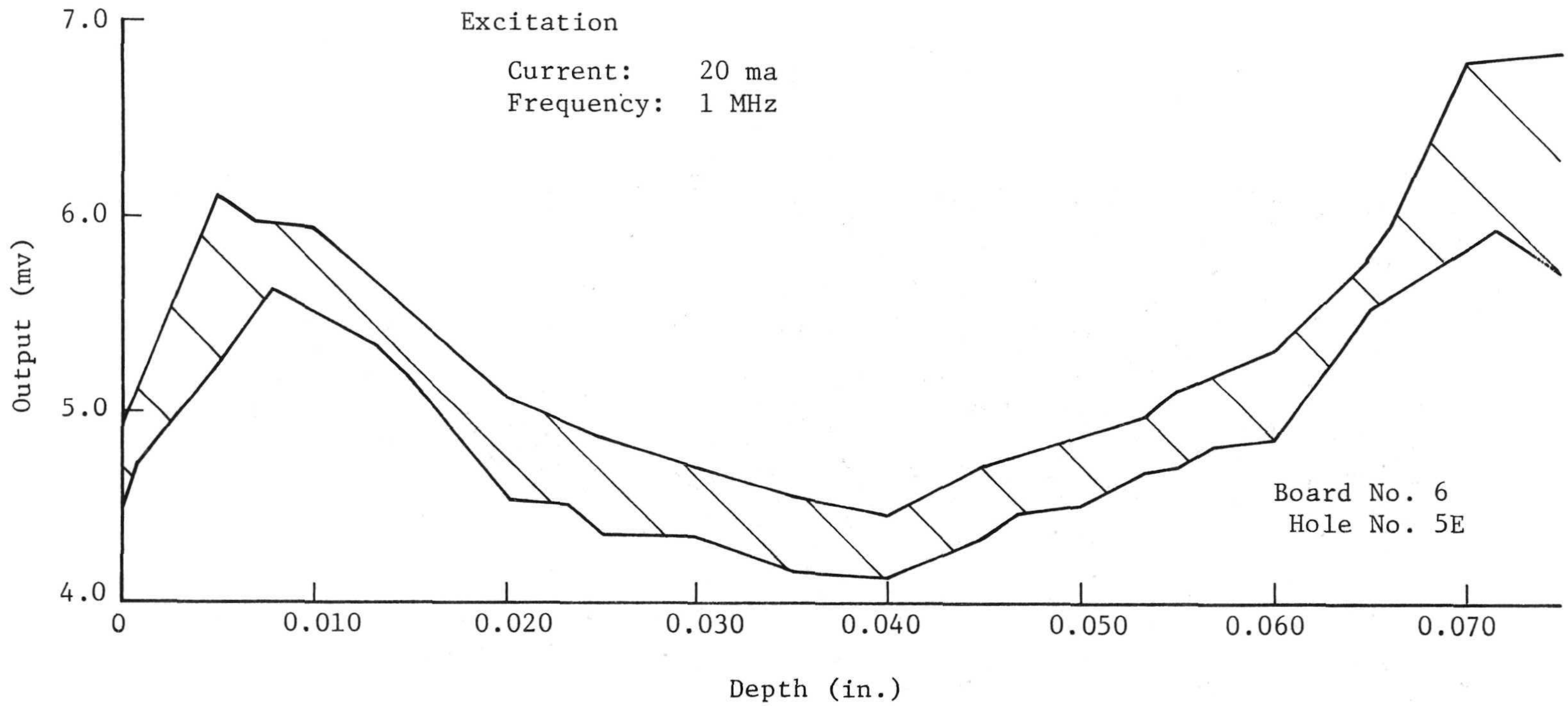


Figure 42. Sensor Output Range with Angular Rotation of 0.060 in. Single Probe in Plated-Through Hole with Smear Defect

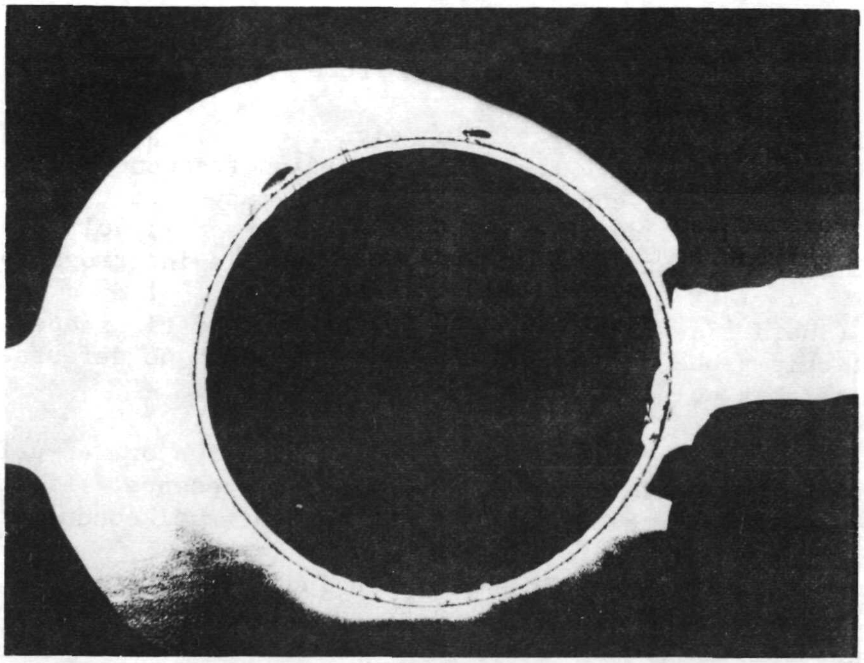

Figure 43. Photomicrograph (36X) of a Cross Section Through the First Internal Pad Showing Separation from Plated-Through Hole Used to Obtain the Data in Figure 42.

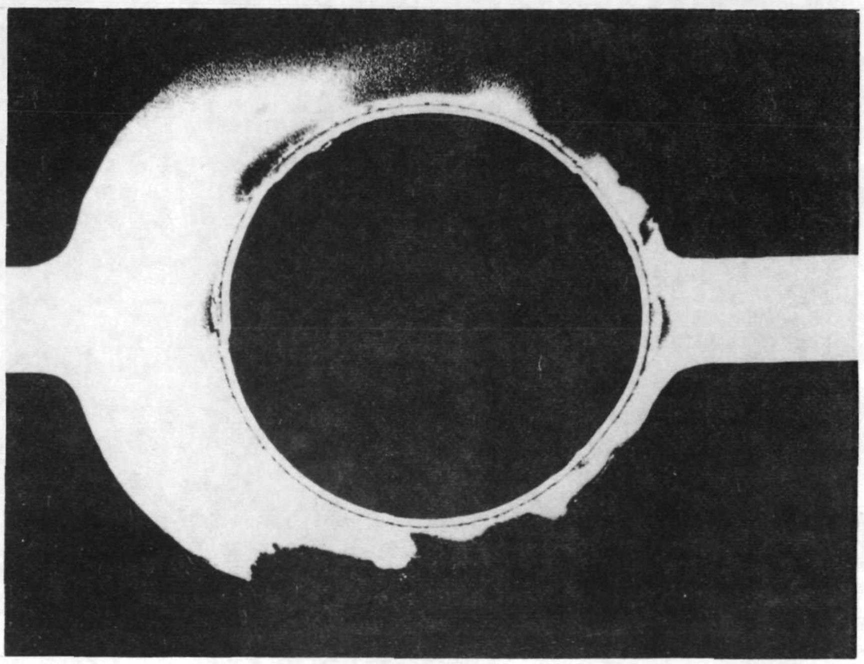

Figure 44. Photomicrograph (36X) of a Cross Section Through the Second Internal Pad Showing Separation from Plated-Through Hole Used to Obtain the Data in Figure 42.

## 0.030 in. Single Probe

The relatively large, direct-coupling signal of this probe drastically reduced its effectiveness. With the test excitation frequency of 700 kHz and a current of 40 ma, the direct coupling of 72 mv was many times larger than the sensor output changes in a test board hole. A differential voltmeter was necessary to read the sensor output voltage during hole interrogation.

Figure 45 (Board 13A, Hole 6C) shows the characteristic shape and sensor output range of this probe in a plated-through hole with no defects. A cross-sectional view of this hole is shown in Figure 46.

An examination of the probe response to a separation or gap defect, Figure 47 (Board 12, Hole 4F), does not indicate its presence. Figures 48 and 49 show large gaps between this hole wall and the internal conductor pads.

Figure 50 (Board 14A, Hole 6E) shows some indication of a defect at 0.060 in. depth. The cross section of this hole shows small voids in the plating near this depth (Figure 51).

Figure 52 (Board 16, Hole 5E) does not appear significantly different from a no defect. The presence of cracks are verified in Figures 53 and 54. The 0.030 in. probe does not exhibit a significant response to defects in plated-through holes, due primarily to its large direct coupling signal.

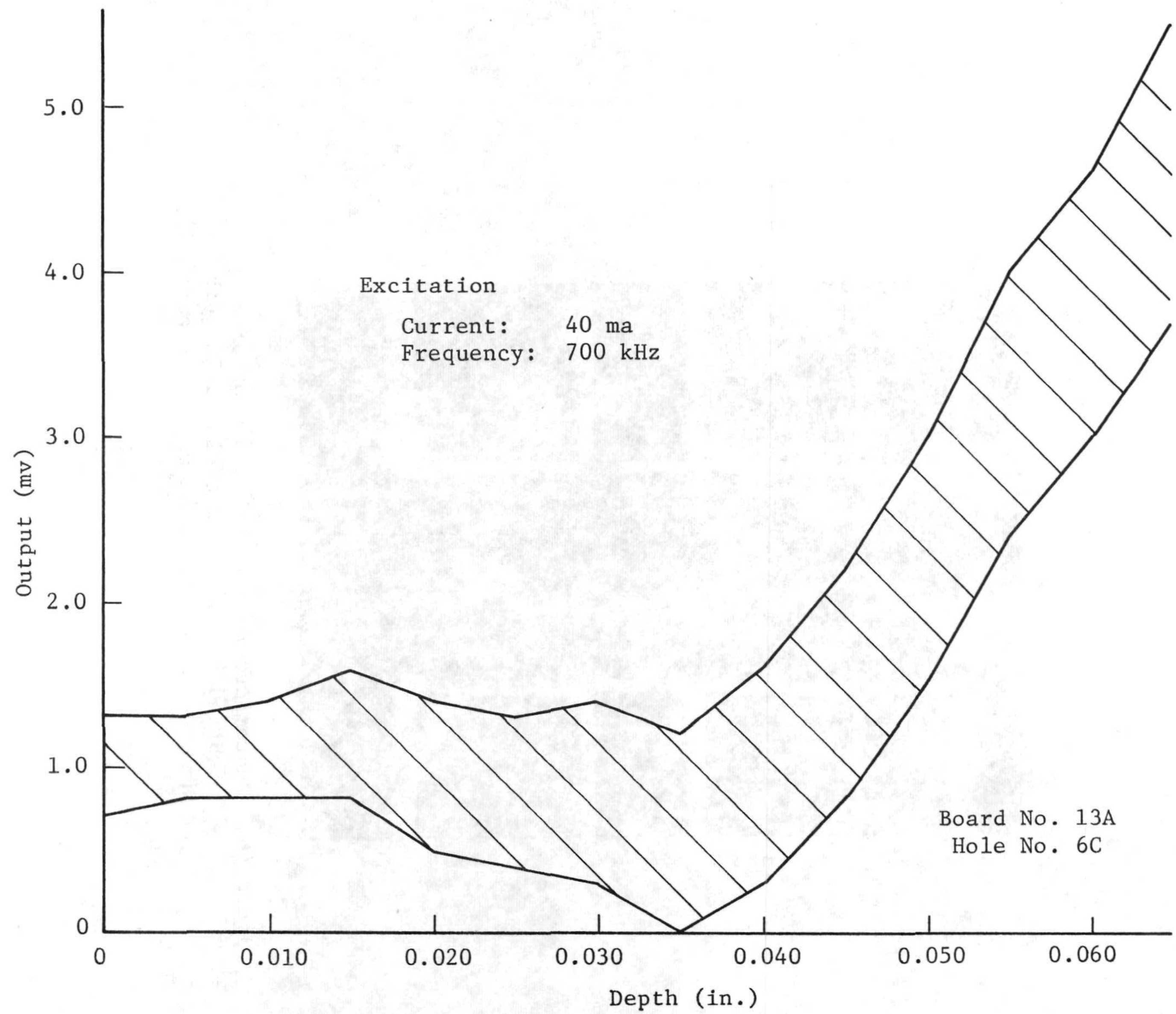


Figure 45. Sensor Output Range with Angular Rotation of 0.030 in. Single Probe in Plated-Through Hole with No Defects

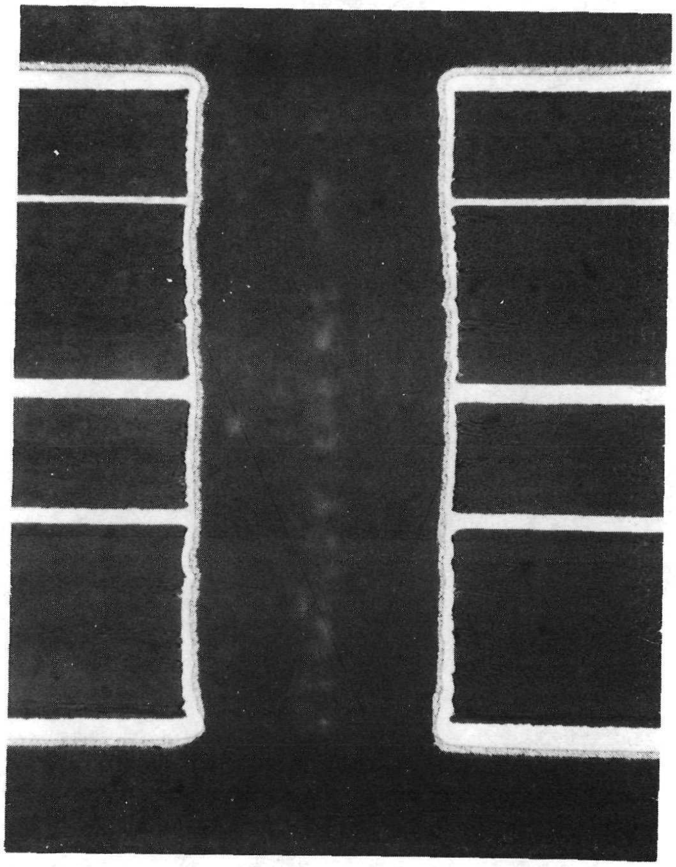

Figure 46. Photomicrograph (36X) of a Cross Section of Standard Defect-Free Plated-Through Hole Used to Obtain the Data in Figure 45.

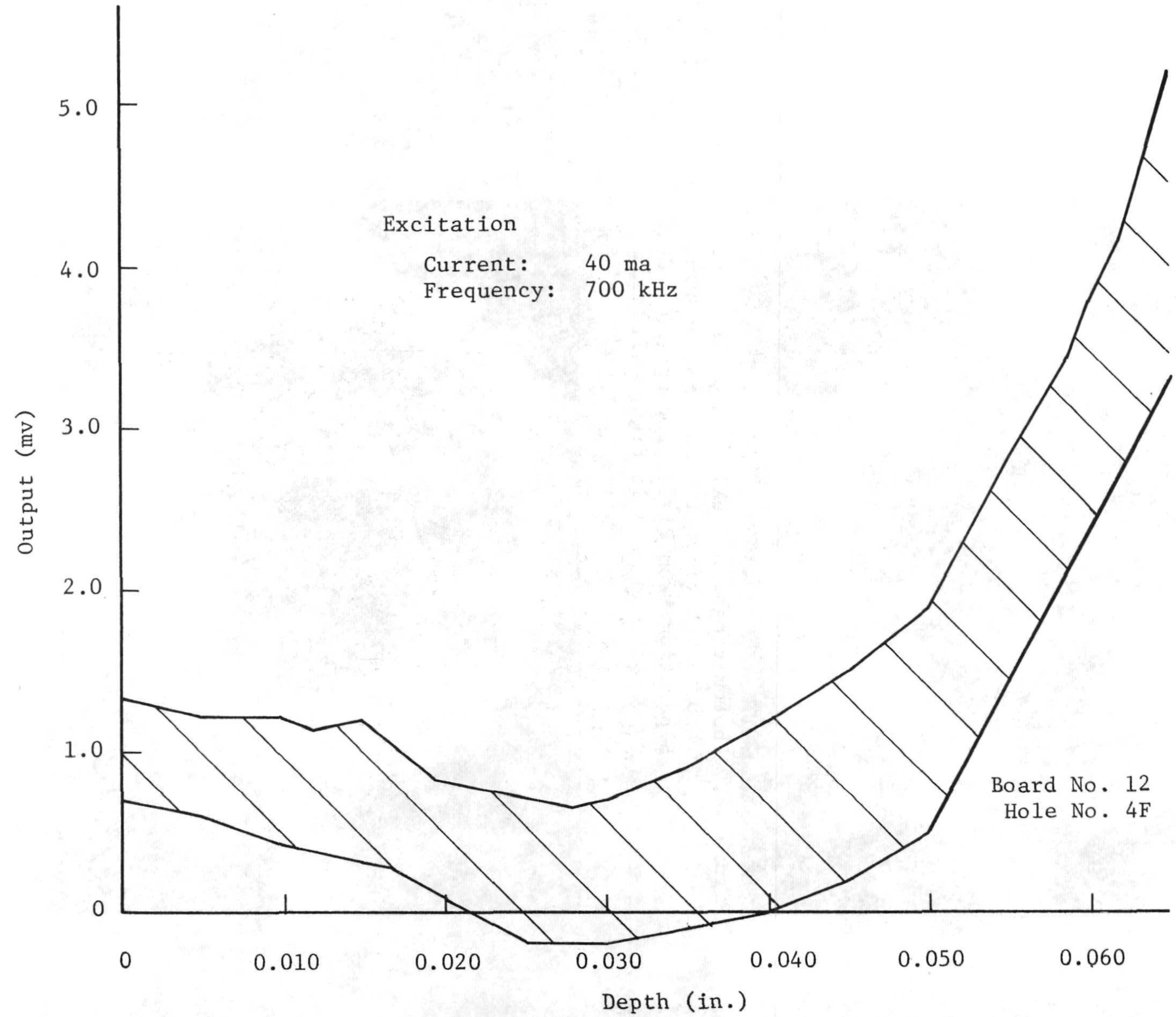


Figure 47. Sensor Output Range with Angular Rotation of 0.030 in. Single Probe in Plated-Through Hole with Gap Defect

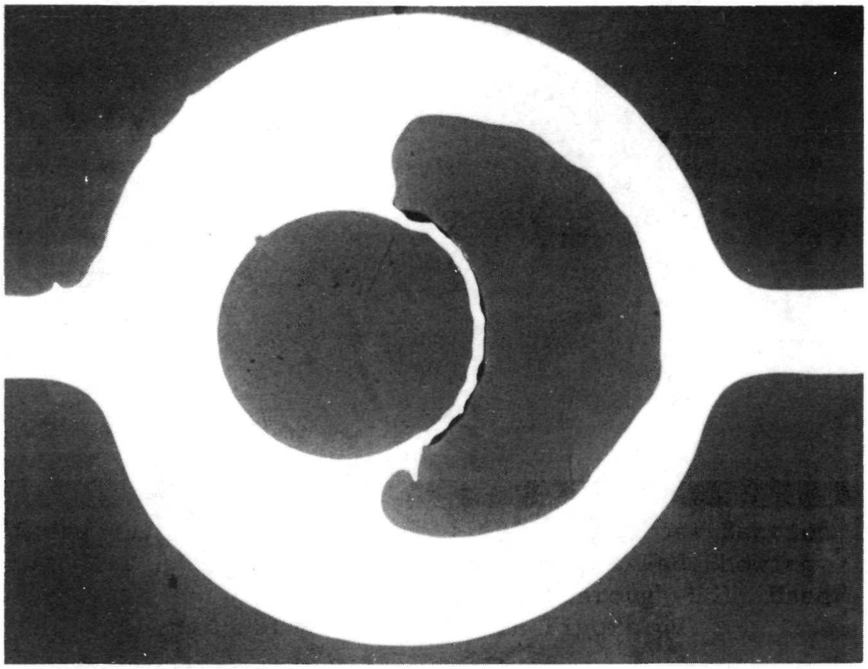

Figure 48. Photomicrograph (36X) of a Cross Section Through the First Internal Pad Showing Separation from Plated-Through Hole Used to Obtain the Data in Figure 47.

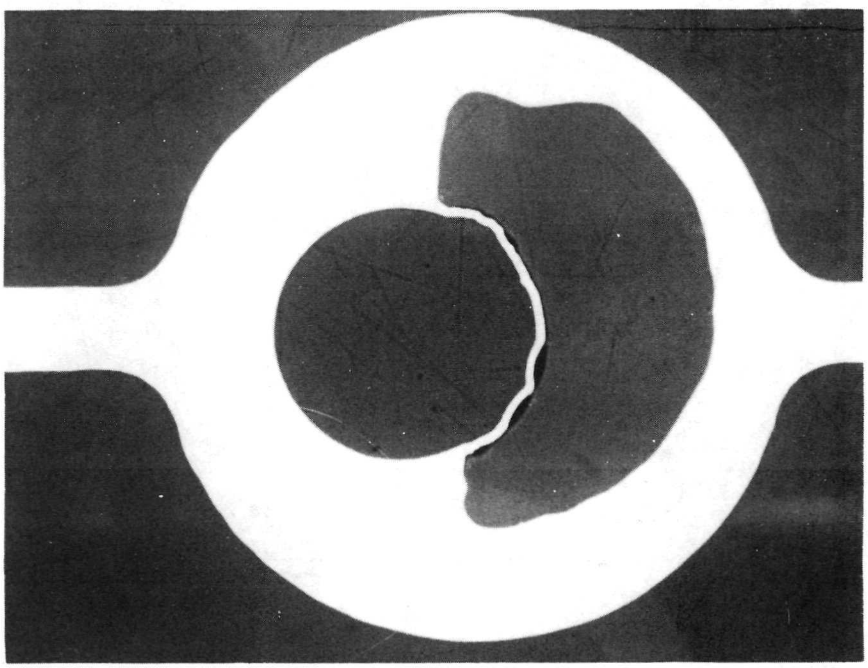

Figure 49. Photomicrograph (36X) of a Cross Section Through the Second Internal Pad Showing Separation from Plated-Through Hole Used to Obtain the Data in Figure 47.

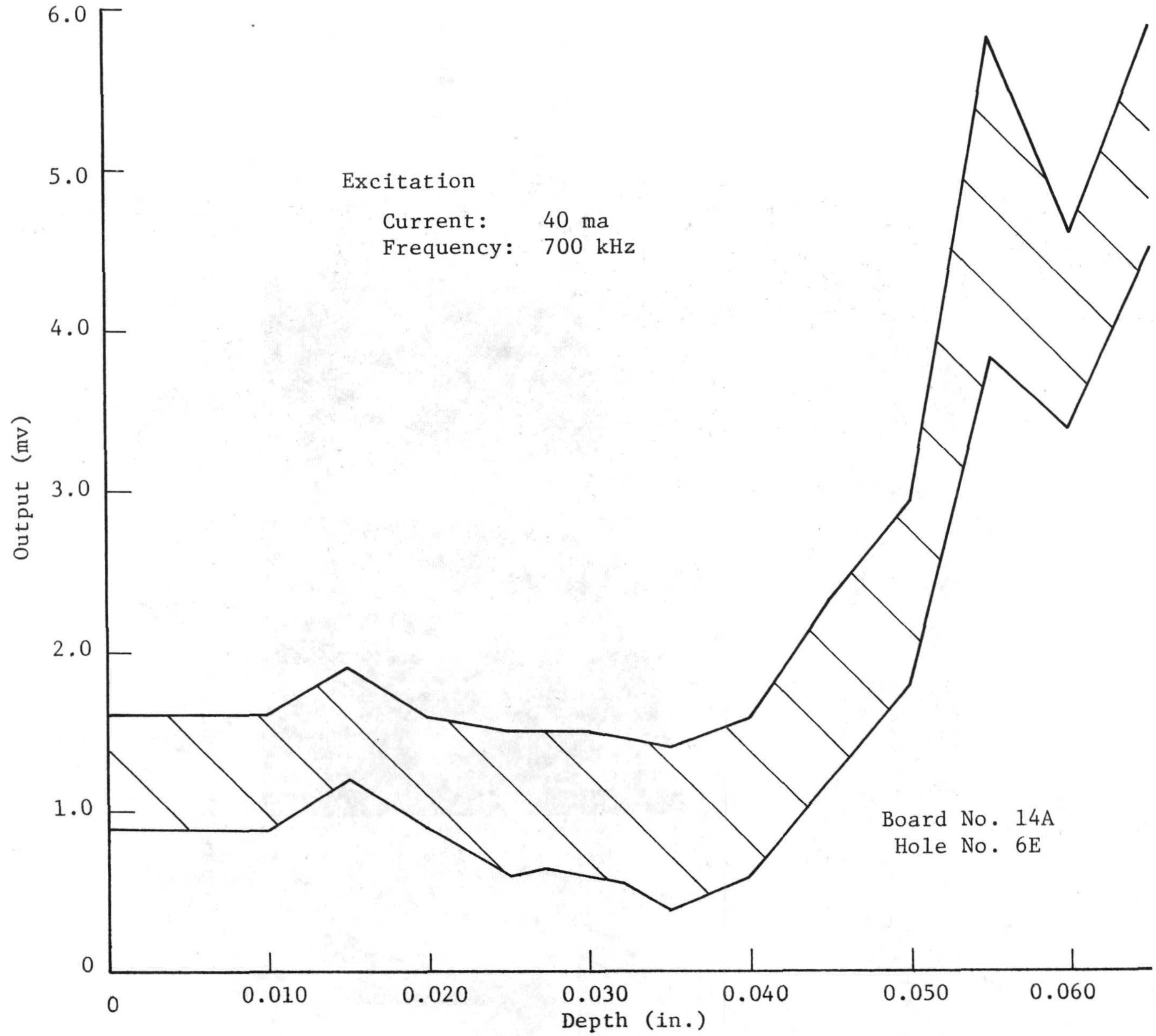


Figure 50. Sensor Output Range with Angular Rotation of 0.030 in. Single Probe in Plated-Through Hole with Void Defect

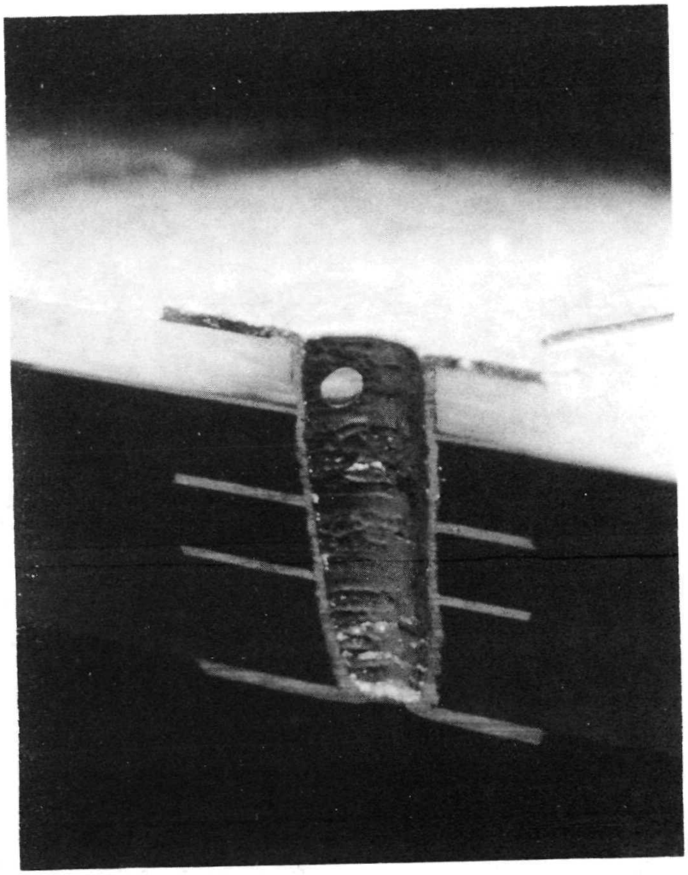

Figure 51. Photomacrograph (24X) of a Section Through Plated-Through Hole with Void Defect Used to Obtain the Data in Figure 50.

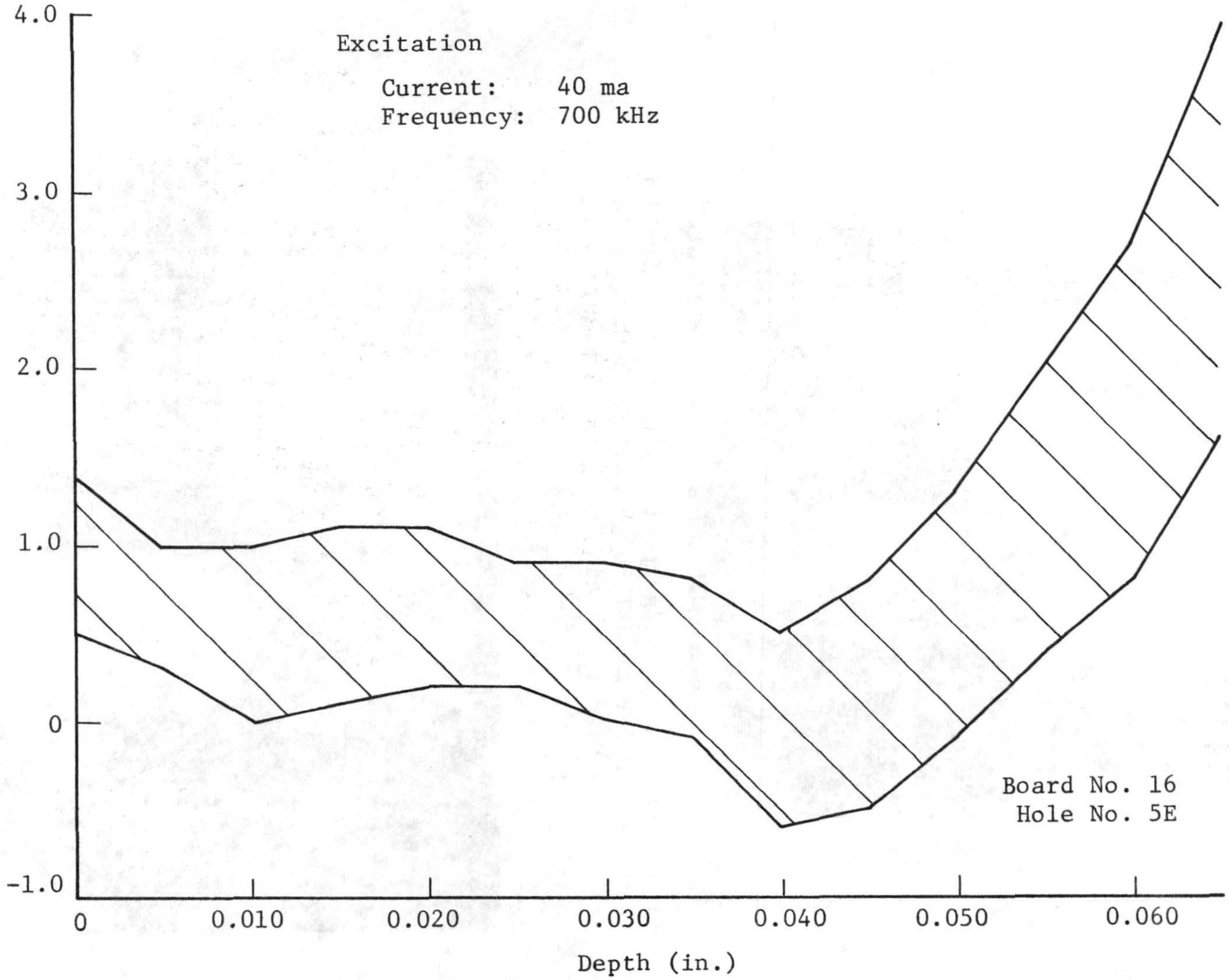


Figure 52. Sensor Output Range with Angular Rotation of 0.030 in. Single Probe in Plated-Through Hole with Crack Defect

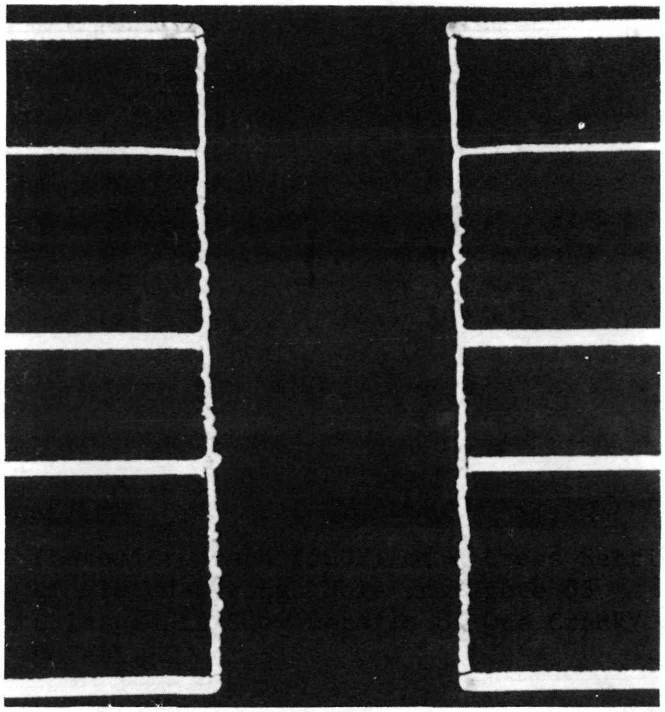

Figure 53. Photomicrograph (36X) of a Cross Section of Plated-Through Hole with Crack Defects Used to Obtain the Data in Figure 52.

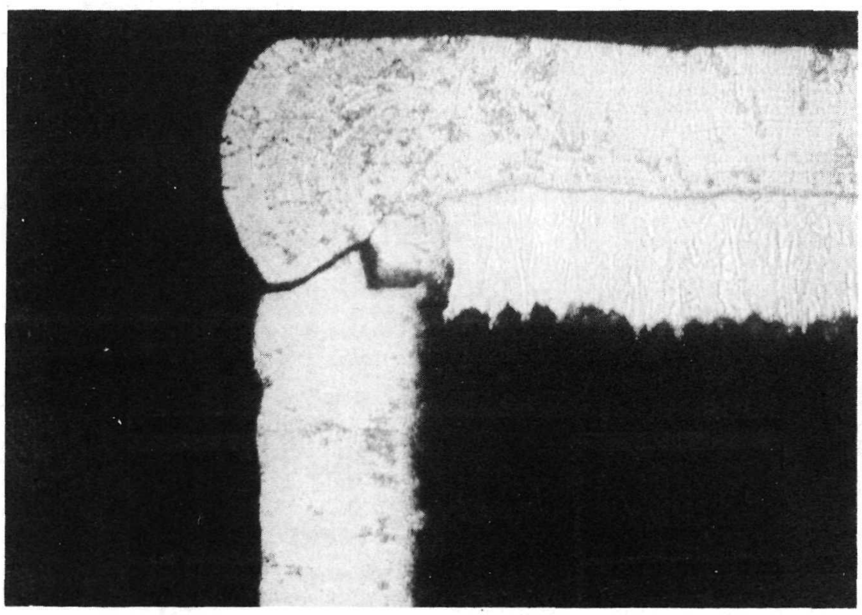

Figure 54. Photomicrograph (500X) of a Cross Section of Plated-Through Hole in Figure 55 Enlarged to Show Details of One Crack Defect.

## 0.060 in. Double Probe

Typical probe response in a plated-through hole with no defects is shown in Figure 55 (Board 3B, Hole 5E). The sensor output bandwidth is consistent and generally linear with probe depth. A cross section of this hole is shown in Figure 56.

Figure 57 (Board 5, Hole 5E) shows the probe response to a void defect centered at a depth of 0.015 in. The variation of sensor output with angular position at this depth is shown in Figure 58. The location of the void is verified in Figure 36.

The probe response to a similar void, but with increased excitation current is shown in Figure 59 (Board 17, Hole 5E). In this figure, the data readings at all eight angular positions in the hole are shown. A differential voltmeter was used to read the sensor output voltage. The increased excitation current caused the direct coupling to increase to 27 mv. The data show a relatively large signal range centered at a depth of about 0.025 in. The location of this void is verified in Figure 60.

Probe response to separation or gap defects is shown in Figure 61 (Board 1, Hole 6D). The sensor output variations at a depth of 0.035 and 0.055 in. indicate defects which are verified in Figures 38 and 39. The small change in sensor signal makes positive identification of the gap defect difficult.

The probe is not usefully sensitive to rough wall defects as shown in Figure 62 (Board 7, Hole 6B). The wall roughness is indicated in Figure 41.

This probe demonstrated a positive detection of voids in the plated-through-hole wall, and to a reduced degree, the detection of gap defects between the wall plating and the pad. The probe showed essentially no response to other defects.

Data from a plated-through hole with crack defects and some separation defects are shown in Figure 63. Even with both types of defects present, the sensor output signals are difficult to interpret and do not appear to give any clear cut indications for positive identification. The overall condition of this plated-through hole is shown in cross section in Figure 64, while Figure 65 is an enlargement to more clearly show one of the crack defects.

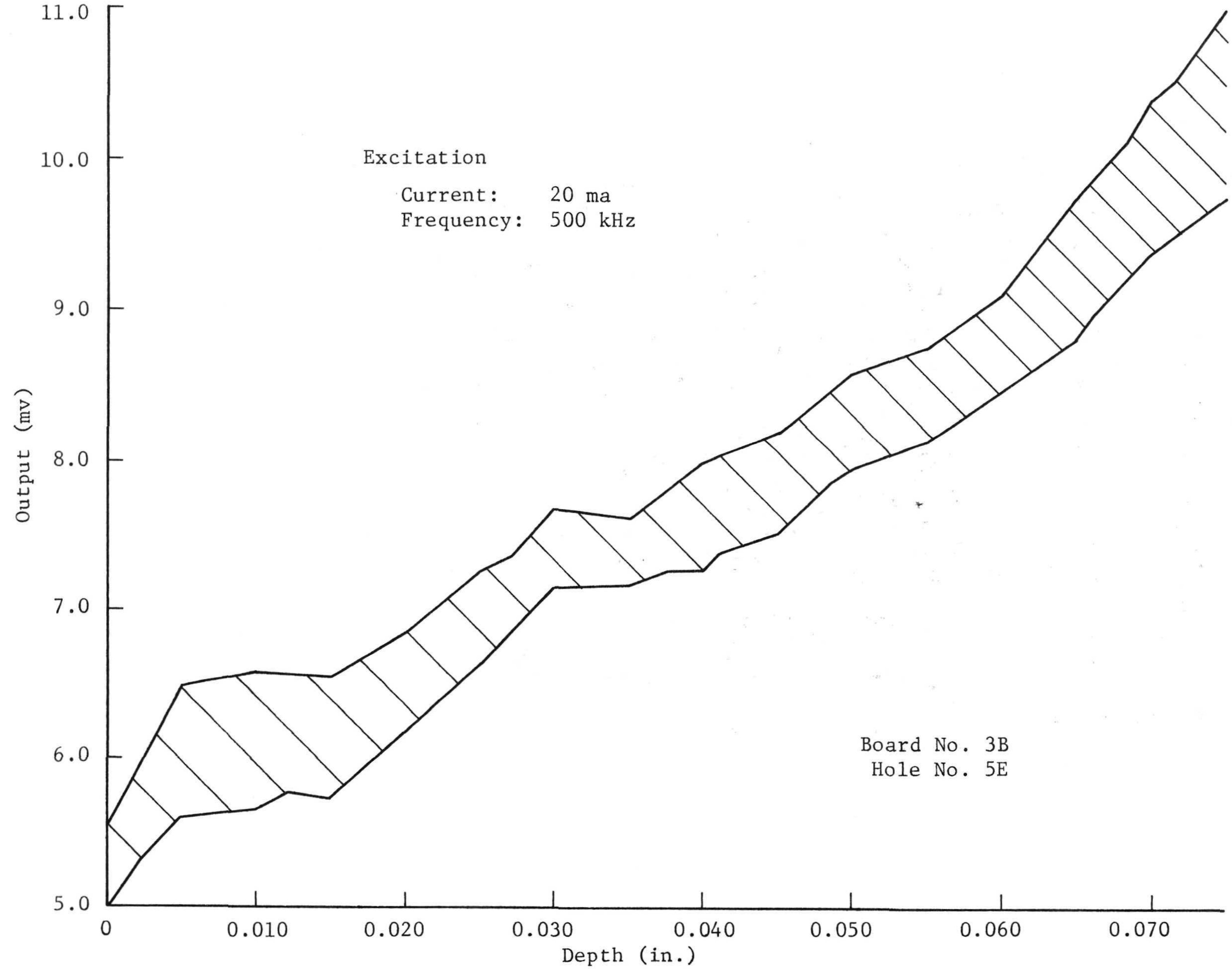


Figure 55. Sensor Output Range with Angular Rotation of 0.060 in. Double Probe in Plated-Through Hole with No Defects

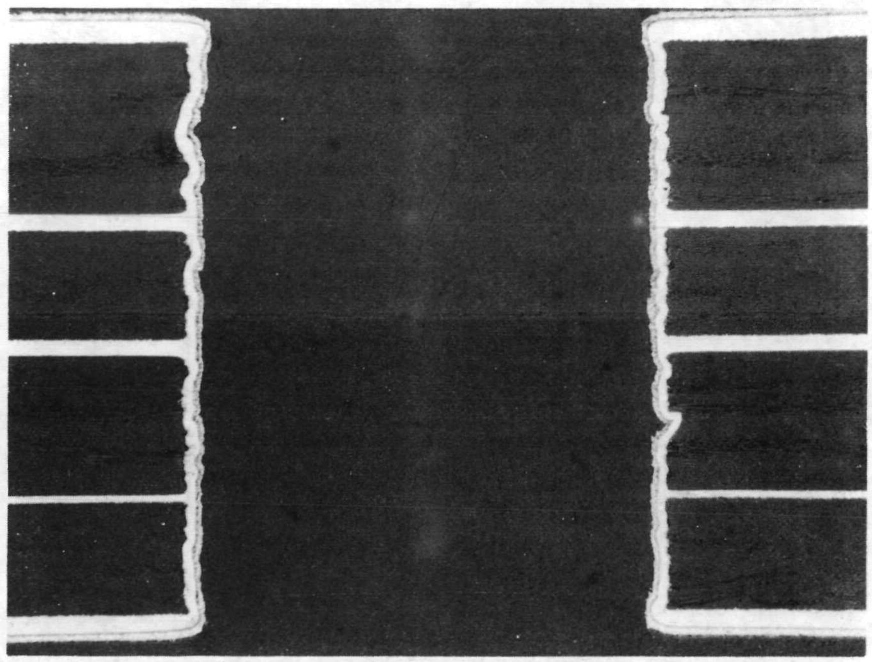

Figure 56. Photomicrograph (36X) of a Cross Section of Standard Defect-Free Plated-Through Hole Used to Obtain the Data in Figure 55.

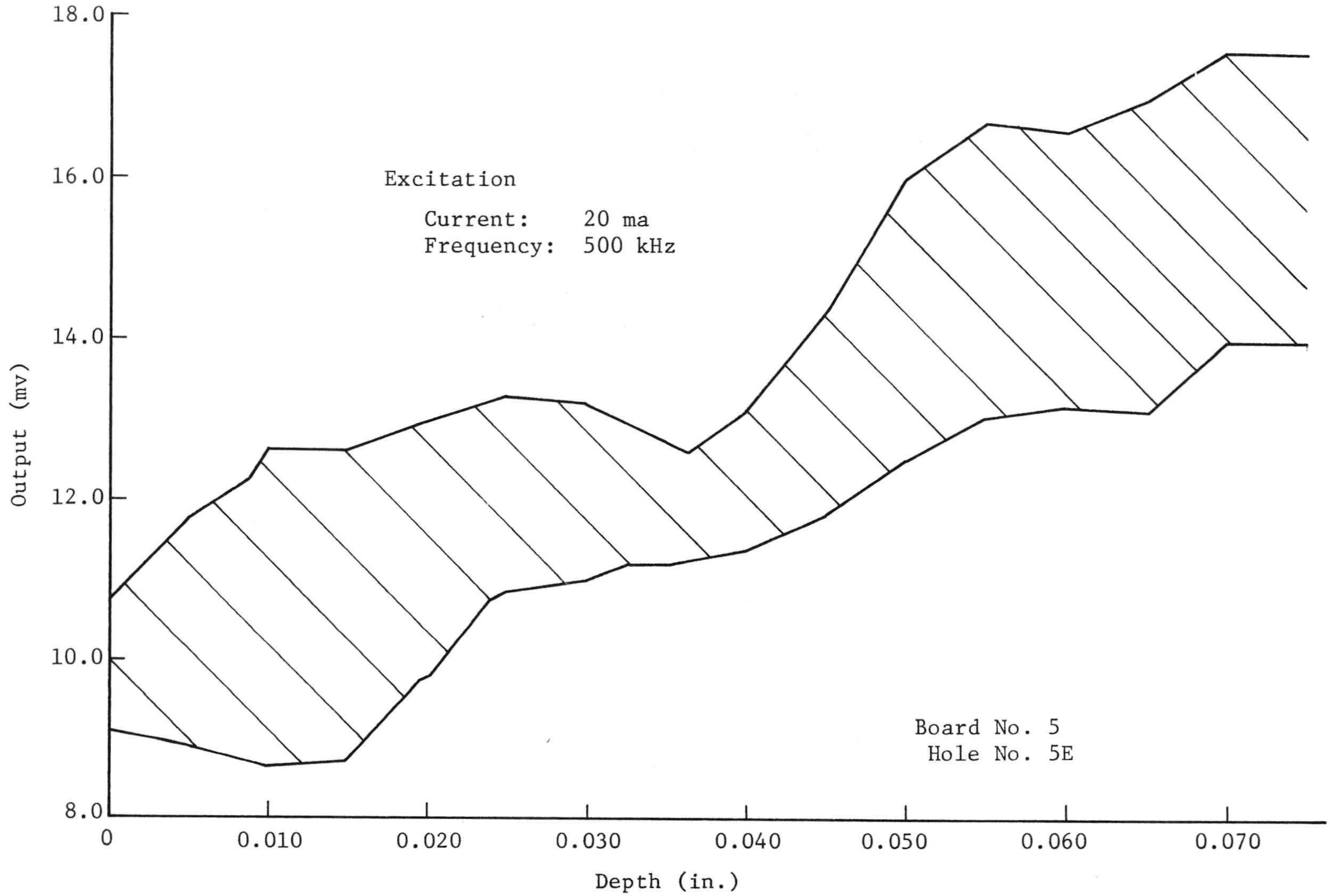


Figure 57. Sensor Output Range with Angular Rotation of 0.060 in. Double Probe in Plated-Through Hole with Void Defect

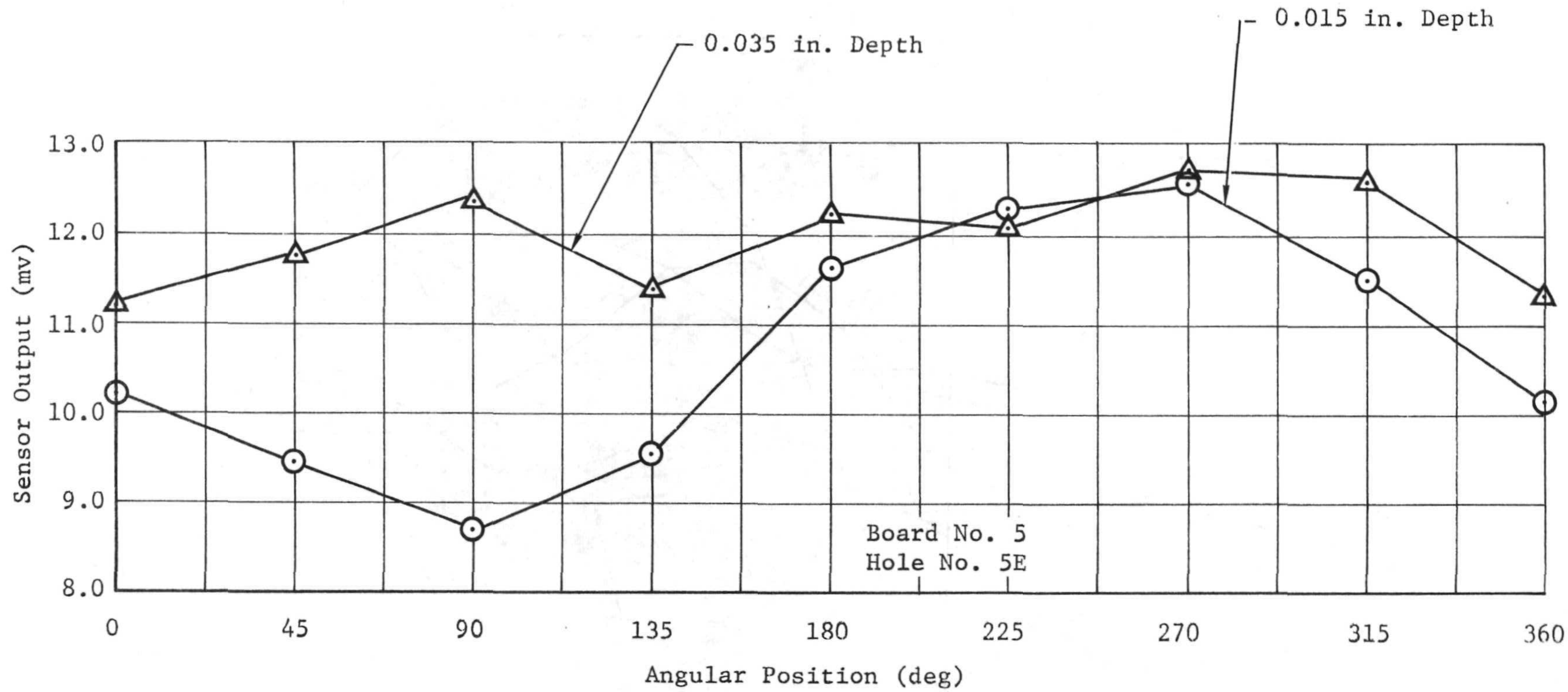


Figure 58. Sensor Output Variation with Angular Position of 0.060 in. Double Probe for Plated-Through Hole Void Defect

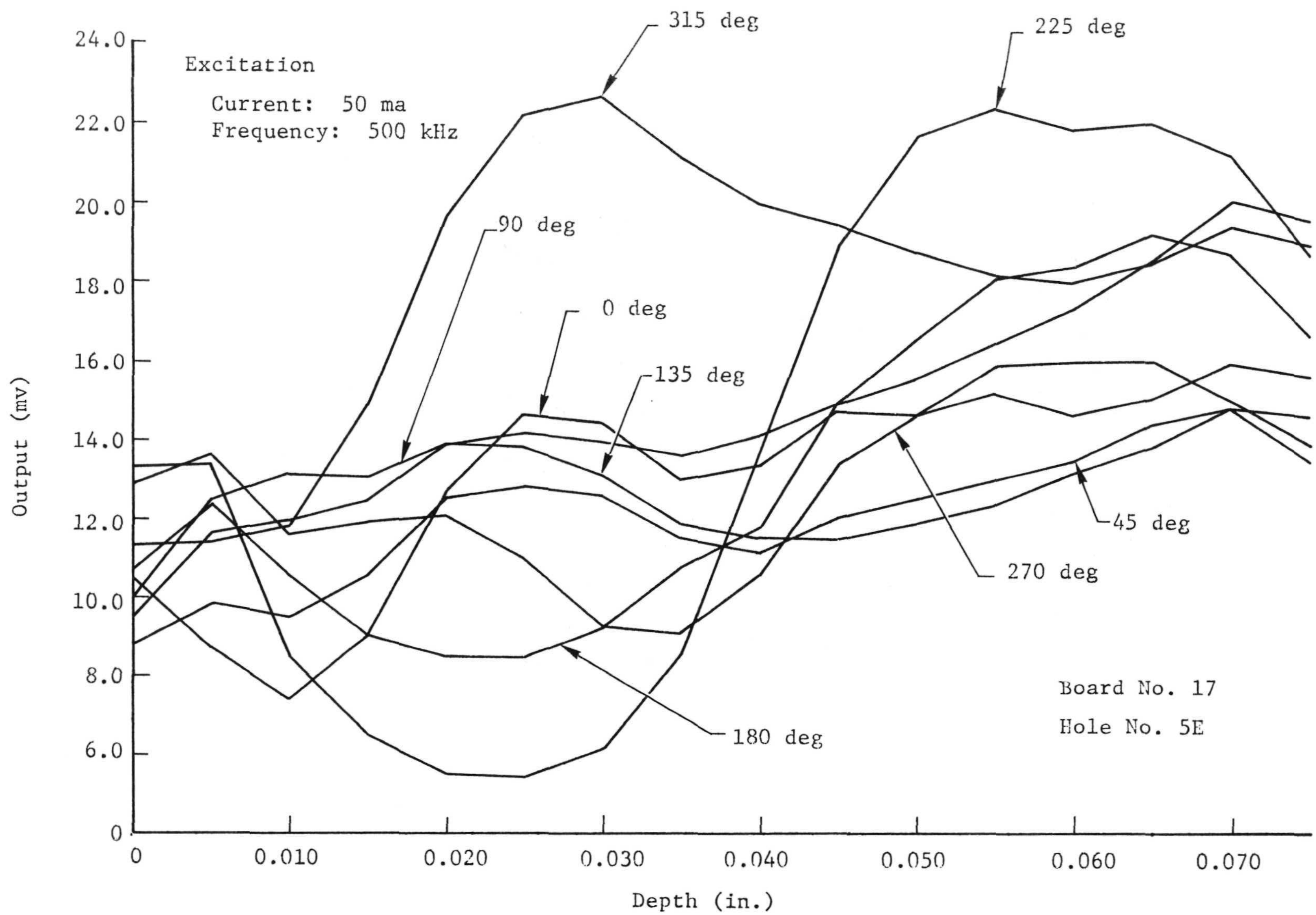


Figure 59. Sensor Output at Eight Angular Positions of 0.060 in. Double Probe in Plated-Through Hole with Void Defect

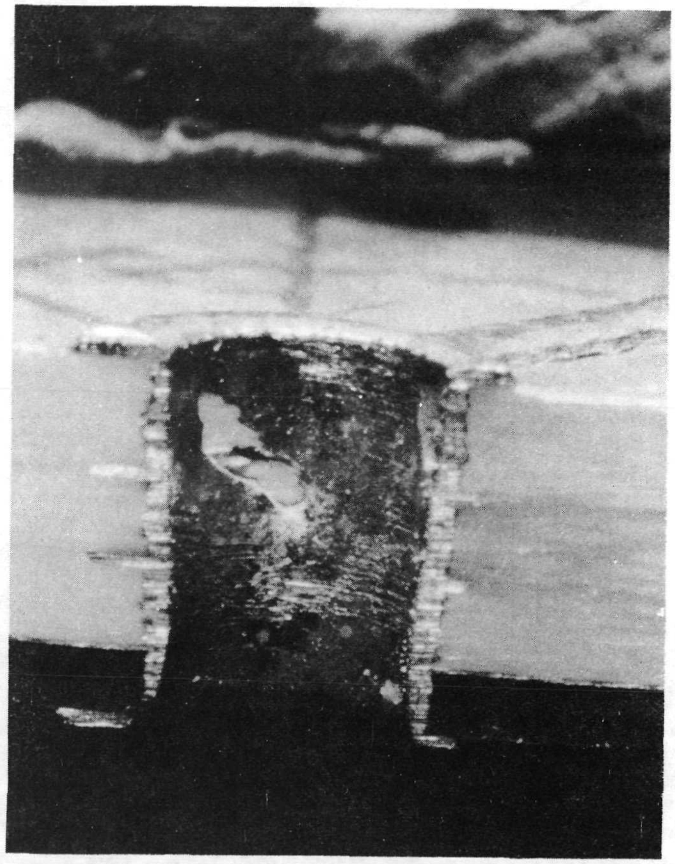

Figure 60. Photomacrograph of Section Through Plated-Through Hole with Void Defect Used to Obtain the Data in Figure 59.

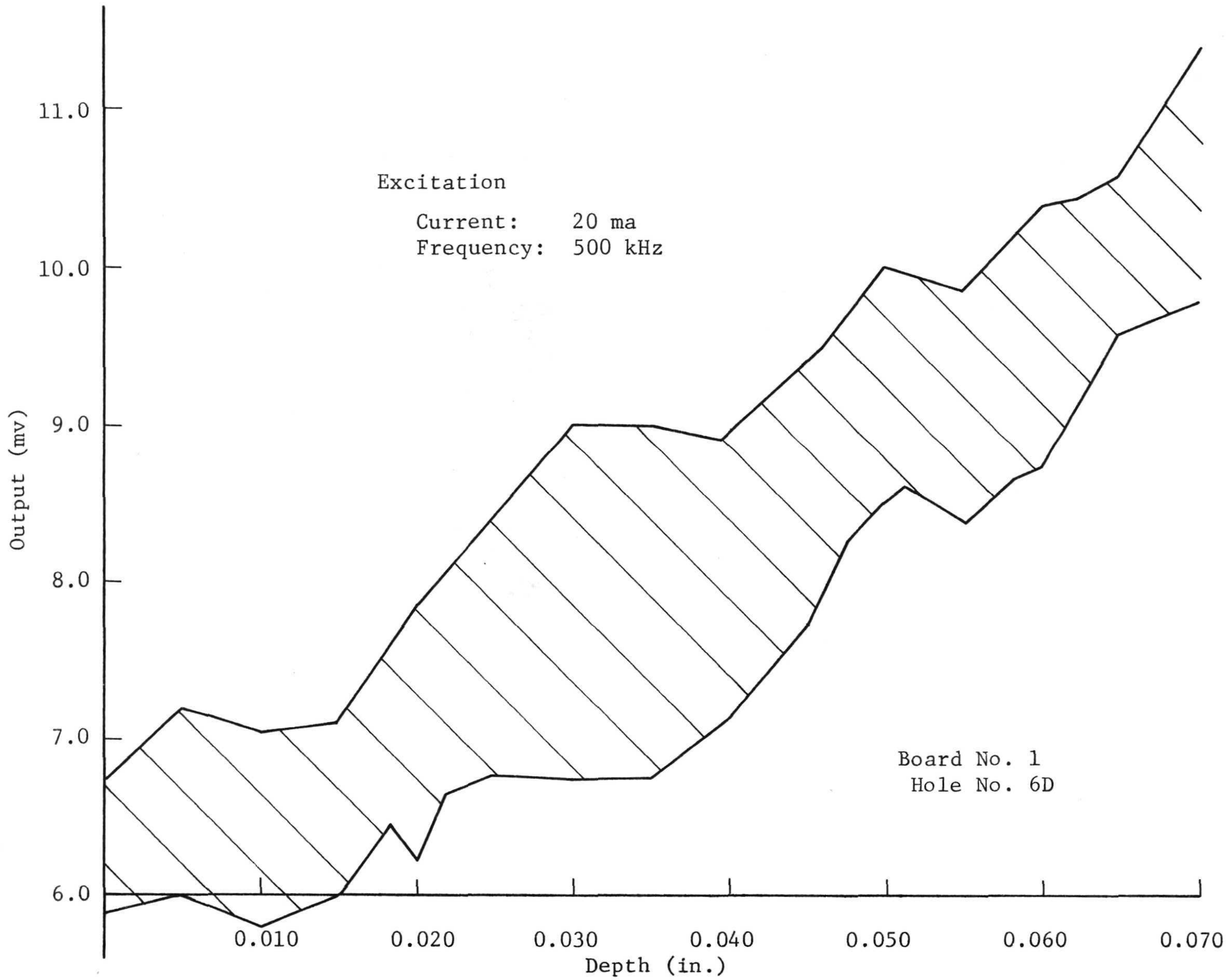


Figure 61. Sensor Output Range with Angular Rotation of 0.060 in. Double Probe in Plated-Through Hole with Gap Defect

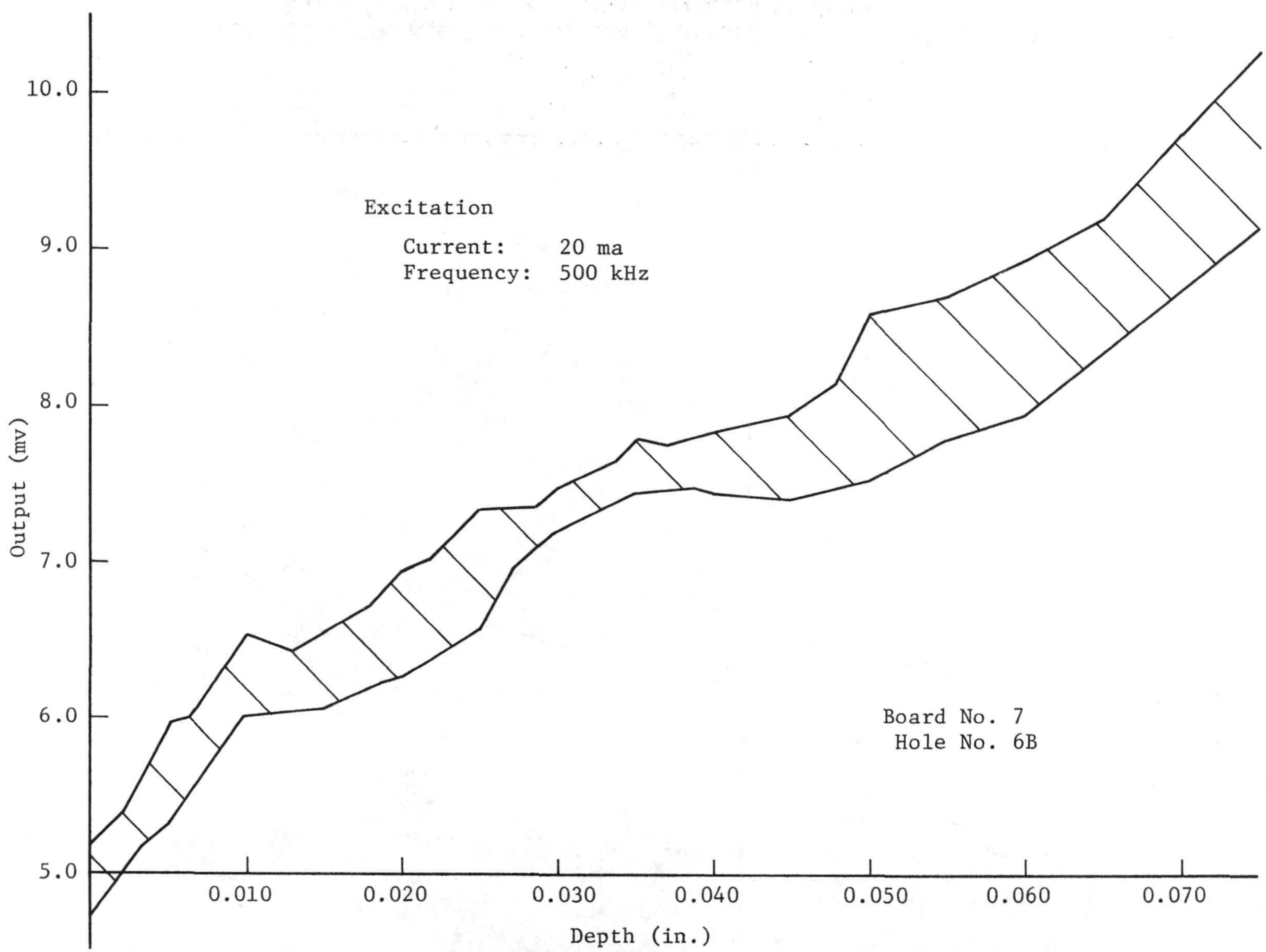


Figure 62. Sensor Output Range with Angular Rotation of 0.060 in. Double Probe in Plated-Through Hole with Rough Wall Defect

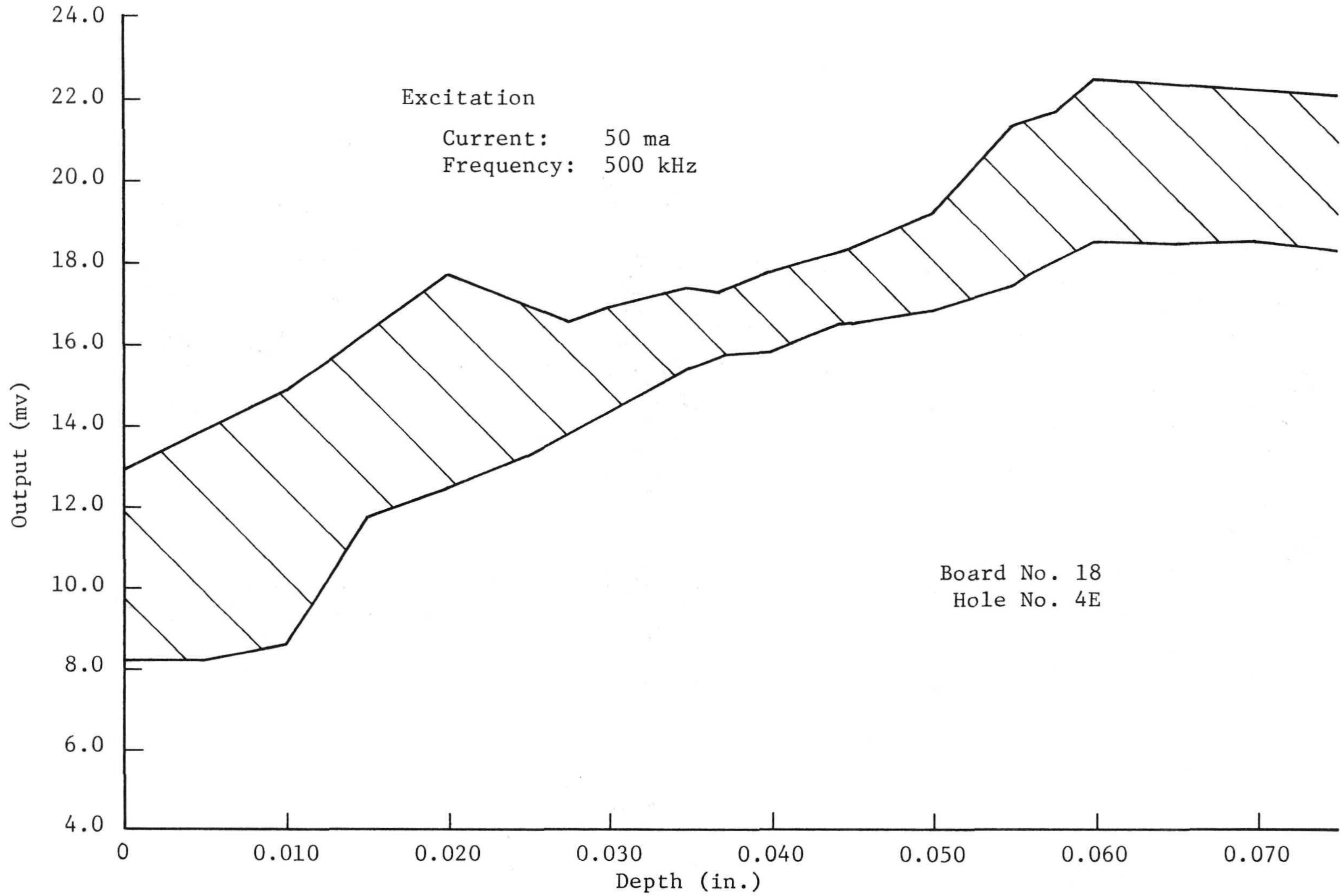


Figure 63. Sensor Output Range with Angular Rotation of 0.060 in. Double Probe in Plated-Through Hole with Crack Defect

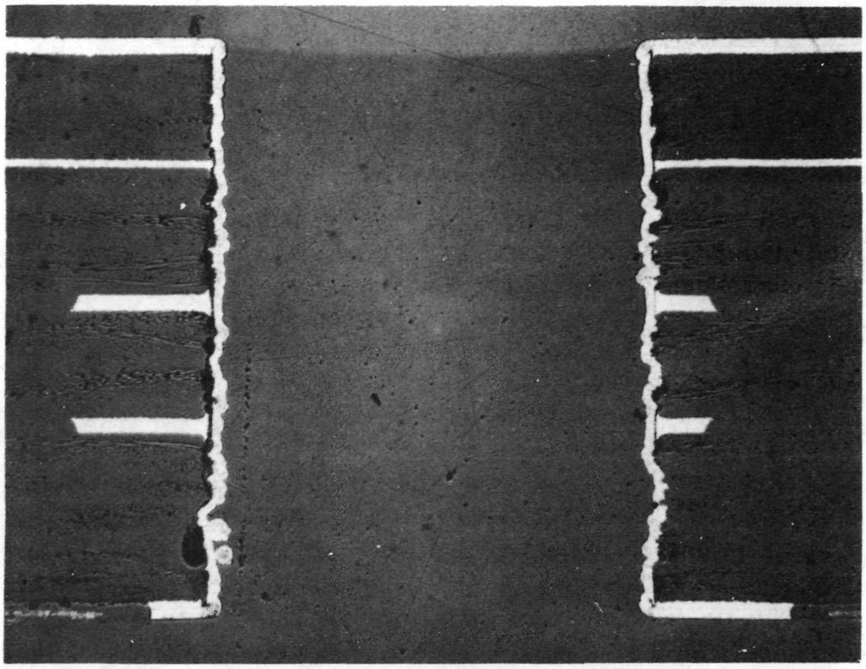

Figure 64. Photomicrograph (35X) of a Cross Section of the Plated-Through Hole with Crack and Separation Defects Used to Obtain the Data in Figure 62.

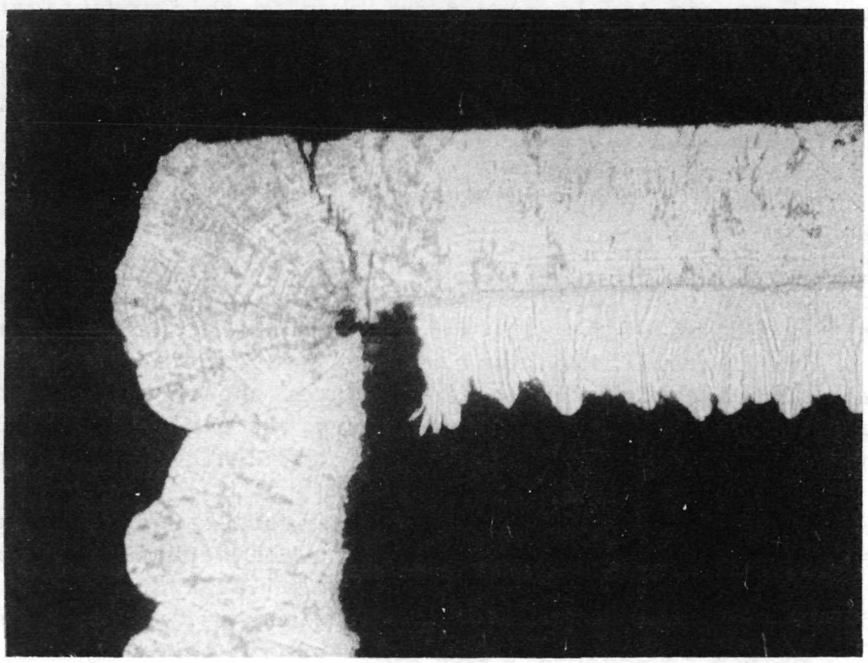

Figure 65. Photomicrograph (500X) of a Cross Section of a Part of the Same Plated-Through Hole as in Figure 63 Enlarged to Show One Crack Defect.

# CONCLUSIONS AND RECOMMENDATIONS

This contract effort represents the first reported attempt to design and fabricate a mutual coupling probe device with magnetic circuitry for the working flux paths. It also was the first known instance where a mutual coupling probe of any type was evaluated by measurements on real plated-through holes in an actual multilayer printed circuit board structure. While the results of the studies described herein are not conclusive with respect to the efficacy of magnetic circuitry mutual coupling probes for nondestructive testing of multilayer board plated-through holes, a considerable amount of original and practical information about such devices was obtained.

The prime conclusion must be that miniature magnetic circuitry devices can be designed and fabricated which do, in fact, function as mutual coupling probes in a manner essentially analogous to the precursor figure "8" coil probe. Further more, the magnetic circuitry probes can generate much higher external excitation fluxes and will pick up much higher coupling signals in the sensor circuit than reported for figure "8" coil devices. Thus, the magnetic circuitry approach does provide mutual coupling probe devices with output signals in the tens-of-millivolts range. Such a relatively high level of signal strength should make possible considerable refinement of performance by further application of engineering techniques.

The fabrication methods developed and employed in this investigation provide a capability for producing miniature magnetic circuitry mutual coupling probes with working tips small enough for insertion into most sizes of plated-through holes in typical multilayer printed circuit boards now in use. A probe with a 0.030 in. diameter tip was demonstrated. By a direct extension of the same processing techniques, it would appear practical to fabricate probes with tip diameters down to about a 0.020 in.

Magnetic circuitry probes of the design developed on this program probably achieve nearly the ultimate in ruggedness and durability. Since the finished probes are a solid structure of ferrite and copper, the mechanical strength is a function only of the overall dimensions and the properties of these materials. The wear resistance is essentially that of the outer sheath of electroplated copper. If greater wear resistance were necessary, it could be readily obtained by a thin overplate of a harder metal such as nickel and/or chromium.

It must be concluded that magnetic circuitry probes as designed and operated on this program are seriously hindered in the detection of the critical plated-through-hole defects by an extremely large mutual coupling signal generated from the overall hole wall itself. This limitation may apply to mutual coupling probes in general. From the present investigation it can only be concluded that the practical usefulness of the magnetic circuitry mutual coupling probes is restricted to testing for the presence of plated-through-hole wall void defects. With the techniques employed to this point, it was not practical to readily identify separation, crack or thin spot type defects in actual multilayer board holes. The problem of the high wall signal is reflected in the extreme sensitivity of the probes to radial and angular position within the hole being tested.

Any recommendations for further development of the magnetic circuitry mutual coupling probe approach to nondestructive testing of multilayer board plated-through hole rest on the possibility of improved utilization of the relatively large output signals which can be obtained with these devices. As can be seen by the results presented in this report, the probes do provide considerable data when used to interrogate a plated-through hole. It is conceivable that the original output signals from the probes could first be refined by incorporation of additional electronics in the excitation and sensor circuits external to the magnetic circuitry. A second general method to be considered would involve the application of more elaborate techniques to the analysis of the raw data produced by the probes.

The best practical solution to the performance problem would be to somehow modify the probe design so that in operation, the device itself would cancel out or reduce the excessive hole wall signal. This was the intent with the "double" probe design attempted in the later stages of the present investigation, but the desired results were not fully realized. A proper extension of this approach should be a fruitful means to improved probe performance. For example, if a technique were developed to center the probe in the hole with the pole faces back from the wall some prescribed distance, the sensitivity to radial position could be overcome and the variations due to placing the pole face areas against the normally uneven hole wall surface would be eliminated. Of course, with the pole faces set back from the hole wall, the probe sensor signal from both the wall itself and any defects present would be considerably reduced. Fortunately, the signal levels with the magnetic circuitry probes are generally so high that considerable reduction can be tolerated, particularly if the ratio of defect signal to good hole background signal could be improved. It is believed that with the probe accurately centered and the pole faces set back from the walls, a "double" probe type design could then be effectively employed to cancel out all or most of the background signal. Additional refinements to improve performance in this respect could possibly be obtained by modifications of the shielding for the probe tip. Also, the size or position of the pole faces could be designed to specially shape the external excitation field across the air gap or to control the coupling sensitivity of the sensor circuit.

If more elaborate electronics or better data analysis could be developed to improve the performance of magnetic circuitry probes for detecting plated-through-hole defects, it would next be appropriate to consider more precise fabrication techniques for the smaller probe sizes. The key consideration here is the fact that the present magnetic circuitry probes do not utilize nearly the full permeability of the ferrite flux paths. Thus, in principle it is possible to design smaller probes and more complex magnetic circuits if the fabrication processes were available. Two such processes were considered but not developed on this program. One is epitaxial reaction deposition of ferrite, and the other is pattern etching of a thin ferrite section. Neither of these processes was practicable for application to the designs developed in the scope of the present contract. However, new design approaches with the ferrite circuits reduced in size to the actual usable capacity could justify the development of these or other precision fabrication techniques.

The experience on the present program indicates that the most direct means to improve the performance of the magnetic circuitry mutual coupling probes would be to overcome the excessive influence of radial position of the probe tip in the plated-through hole. The sensitivity to radial position made it necessary to have the probe tip pole faces in contact with the hole wall for each measurement. This in turn maximized the large mutual coupling signal from the normal hole wall which tends to mask the defect signals.

It is felt that the best solution to these basic problems would be to maintain the probe tip pole face areas some predetermined finite distance away from the plated-through-hole wall during interrogation. Preliminary considerations suggest that this could best be accomplished by making the probe tip sufficiently smaller in diameter than the hole size to be tested and then maintaining the probe co-axial with the hole as mutual coupling measurements are taken. It would be necessary to fabricate the probes with the tips closely co-axial with the body to facilitate alignment fixturing. Also, a mechanism would be needed to accurately center the plated-through hole with the probe. A system analogous to a bottom-drilling machine should be suitable, where a tapered pin which is co-axial with the probe tip engages the plated-through hole from below for precise positioning. Further, the fixturing system should be mechanized to provide the necessary movements of the probe and the hole during interrogation.

Based on probe data from the present program and on general mechanical engineering technology, the dimensions and tolerances required for the above approach appear feasible. The key factor is that measurements on the magnetic circuitry probes revealed that the wall signal falls off very rapidly as the probe tip pole face areas move away from the wall. However, after the probe tip is separated from the wall by several thousandths of an inch, the change in the wall voltage is much less with additional increase in distance. Of course, with the pole faces back from the wall far enough to reduce the sensitivity to distance, both the wall signal and any defect signal are decreased considerably. This would not present a serious problem with the magnetic circuitry probes because of the relatively high initial signal levels. What should be obtained by this approach is a smaller but more constant background wall signal so that the signal from a defect, even though smaller in absolute value, would be relatively much more pronounced and more readily detectable. In summary, it would apparently be necessary to first fabricate a well aligned probe with a tip diameter about 0.010 in. smaller than the holes to be tested. Then fixturing would have to be prepared to insert and rotate the probe tip in the holes so that the distance between the surfaces of tip and the hole wall did not vary more than about 0.002 in. during measurements.

This method of centering the probe in the holes with the pole faces a fixed distance away from the walls could be applied fruitfully to both the "single" and "double" probe designs. However, the greatest utility could probably be obtained with the double probe type. Part of any further effort should include optimizing the ferrite material and the shape of the excitation circuit air gap, and further reducing the direct coupling in these probes.

It would be very desirable to be able to interrogate a plated-through hole on a GO/NO-GO basis by simply inserting the probe in a single motion without the need to take numerous discrete readings at different depths and angles. Such a result could possibly be obtained with an optimized double probe operated by centering in the hole as proposed above. However, with only two mutual coupling areas, some defects could be missed with a double probe. A new design is suggested which should increase greatly the scanning power of the device. This would be a magnetic circuitry probe tip with four excitation air gap areas spaced equidistant around the circumference. Such a configuration could be readily fabricated along the same lines as the previous double probe by simply using two double excitation circuits, one for each half of the probe. The sensor circuit of the new design would consist of a single coil wound circumferentially on the probe tip so as to lie between the pole faces of each pole-face pair in the excitation circuits. The basic principle of operation would be the same as present mutual coupling probe designs, however, shielding and direct coupling considerations would obviously be different. There would be no need to shield the four excitation circuits from each other, but careful attention would be given to positioning of the sensor winding so as to minimize direct coupling. Since the sensor winding is symmetrical, probes of this new design would not be sensitive to the angular position of any defect, but should be more effective for rapidly distinguishing abnormal holes, in general.



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